Received July 19, 2015, accepted July 27, 2015, date of publication September 14, 2015, date of current version October 22, 2015.

Digital Object Identifier 10.1109/ACCESS.2015.2476996

Electric Vehicle Charging on Residential Distribution Systems: Impacts and Mitigations

ANAMIKA DUBEY, (Student Member, IEEE), AND SURYA SANTOSO, (Fellow, IEEE)
Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin, TX 78712, USA

Corresponding author: S. Santoso (ssantoso@mail.utexas.edu)

ABSTRACT This paper aims to understand, identify, and mitigate the impacts of residential electric vehicle (EV) charging on distribution system voltages. A thorough literature review on the impacts of residential EV charging is presented, followed by a proposed method for evaluating the impacts of EV loads on the distribution system voltage quality. Practical solutions to mitigate EV load impacts are discussed as well, including infrastructural changes and indirect controlled charging with time-of-use (TOU) pricing. An optimal TOU schedule is also presented, with the aim of maximizing both customer and utility benefits. This paper also presents a discussion on implementing smart charging algorithms to directly control EV charging rates and EV charging starting times. Finally, a controlled charging algorithm is proposed to improve the voltage quality at the EV load locations while avoiding customer inconvenience. The proposed method significantly decreases the impacts of EV load charging on system peak load demand and feeder voltages.

INDEX TERMS Electric vehicle charging, TOU pricing, controlled charging, power quality, voltage quality, distribution system, dynamic programming.

I. INTRODUCTION

The promise of clean and efficient transportation coupled with the advances in battery technologies and generous federal incentives are promoting transportation electrification [1]–[4]. In the near future, electric vehicles (EVs) are expected to dominate the vehicle market. However, the success of EV technology depends on the availability of EV charging stations. To meet this demand, utilities are installing EV charging stations at residential and commercial locations. A residential EV charging station in North America provides a 120V (Level-1) or a 240V (Level-2) voltage supply to the connected EV through either a normal wall outlet or a dedicated charging circuit. Commercial chargers are generally high-powered, fast AC/DC chargers and installed in heavy traffic corridors and at public charging stations. However, because commercial chargers are still in the primary stages of deployment, EV owners typically charge their EVs overnight at residential charging stations primarily using Level-2 chargers. Unfortunately, the increasing number of residential EV chargers may cause several challenges for the distribution system. Therefore, both a system level analysis of the impacts of EV integration on the residential distribution circuit and solutions to address their impacts are needed.

EV integration studies in the literature have primarily focused on evaluating the impacts of EV loads on 1) electricity generation adequacy [4]–[10], 2) transformer aging [10]–[14], and 3) distribution system power quality [10]–[28]. In section II, a short literature review of these three issues is presented. In short, it is speculated that if charging infrastructure is not planned properly, the widespread adoption of EVs over the distribution circuit can significantly increase the substation load demand. In turn, the generation capacity of the existing distribution grid may need to be expanded. Furthermore, the increased peak load demand due to EV load charging may overload service transformers, resulting in transformer overheating, thus deteriorating the transformer's life and increasing the economic burden on distribution utility companies. Finally, increased EV penetration may result in sustained secondary service under-voltage conditions, violation of under-voltage limits, and three-phase power supply unbalance, which would deteriorate the service voltage quality.

In the literature, several methods are proposed to mitigate the impacts of EV charging on the distribution grid. The mitigation strategies are primarily grouped into two categories. In the first approach, utilities indirectly control EV charging using Time-of-Use (TOU) pricing [29]–[36]. The decreased off-peak electricity rates in a TOU pricing scenario motivates EV owners to charge their vehicles during off-peak hours. This method significantly decreases the peak load demand and mitigates transformer overloading and heating concerns. In the second approach, utilities directly control EV charging rates and charging start time using smart charging algorithms [15], [37]–[55]. To date, algorithms proposed to control EV load charging aim to achieve two objectives. One objective is to maximize utility benefits by shifting EV charging to off-peak load hours. The other objective is to maximize customer benefits by optimally charging EVs aiming to decrease the total electricity cost in a real-time electricity market. However, both smart charging methods have certain limitations. For example, by shifting the EV charging profile to off-peak hours, the first method ignores customer inconvenience. As for the other method, many utilities still do not use real-time electricity pricing for their residential customers, rendering the method inapplicable. Furthermore, none of the smart charging methods directly aim to decrease the impacts of EV charging on feeder voltages.

A. CONTRIBUTION

The objective of this paper is to identify, understand, and mitigate the impacts of EV load charging on a residential distribution circuit. A detailed literature review including EV charging impacts and their solutions is presented first. Next, an approach to evaluate the impacts of EV load on the distribution system is presented. Additionally, several mitigation schemes that address EV charging concerns are also discussed including infrastructural upgrades, indirect EV charging control using TOU pricing, and direct EV charging control using smart charging algorithms.

The proposed EV impact analysis approach identifies several factors that affect primary and secondary distribution voltage quality while EV loads are charging. These factors include EV load location, size, distribution, and percentage penetration. The impacts of EV charging are evaluated for both a typical North American (NA) and a typical European (EU) distribution circuit [28]. The EV charging impacts on both NA and EU distribution circuits are compared. The study concludes that EV load charging may increase the system peak load demand, result in service transformer overloading, and may cause unnecessary voltage drops in the secondary service voltages.

Given the impact of EV charging on transformer loading and service voltage quality, the paper suggests the following infrastructural upgrades to mitigate EV load concerns: increase the size of the service transformer and reconfigure the distribution circuit using an additional service transformer. However, because infrastructural upgrades require significant labor and cost, in order to mitigate EV load concerns the paper also presents both indirect and direct control algorithms for EV charging. The impact of indirectly controlling EV charging with TOU pricing is discussed first. Next, a method is proposed to identify an optimal time to begin off-peak rates in a TOU pricing scenario, while avoiding EV customer inconvenience. It is observed that the simultaneous charging of EV loads during off-peak hours under a TOU schedule may result in a second peak in the load demand and unnecessary additional voltage drops. To address this concern, a smart charging algorithm is proposed to directly control EV charging rates and charging start time while minimizing the voltage variations at each EV load location. By minimizing voltage variations, the proposed algorithm shifts the EV load demand to off-peak load hours, thus mitigating loading concerns as well.

B. PAPER ORGANIZATION

The rest of the paper is organized as follows. Section II presents a literature review on evaluating and mitigating the impacts of EV charging on the utility distribution system. A short discussion on EV technology and charging standards is presented in Section III, followed by our approach to evaluating the impacts of EV charging on distribution voltage quality in section IV. Methods to mitigate EV load impacts by upgrading the infrastructure are detailed in Section V. The proposed methods of controlling EV charging, indirectly using TOU pricing and directly using smart charging algorithm, are presented in Sections VI and VII, respectively. Section VIII summarizes the findings and presents the conclusion.

II. EVALUATING AND MITIGATING THE DISTRIBUTION SYSTEM IMPACTS OF EV CHARGING – A LITERATURE REVIEW

This section presents a detailed literature review on the impacts and mitigation of EV charging on the distribution system. The impact analysis details the EV charging impacts on the existing distribution circuits' generation adequacy, transformer aging due to overloading, and distribution system power quality. Several mitigation schemes proposed in the literature, including indirect control using TOU rates and direct control using smart charging algorithms, are detailed next.

A. IMPACTS OF EV CHARGING ON DISTRIBUTION SYSTEM

Growing EV charging infrastructure poses several challenges for the existing distribution system. These challenges have been thoroughly evaluated in the past few years. In the existing literature, EV impact analysis is primarily conducted to evaluate the effects of EVs on electricity generation adequacy, transformer aging, and distribution system power quality. It is speculated that EV charging during peak load hours may increase the peak load demand and necessitate generation capacity expansion. Additionally, increased EV load demand may overload substation and service transformers, thus deteriorating the transformers' life. Furthermore, EV charging may result in several power quality issues such as voltage drops, power unbalances, and voltage/current harmonics.

1) EV LOAD IMPACTS ON ELECTRICITY GENERATION ADEQUACY

Several EV integration studies [4]–[10] have analyzed the existing and planned generation capacity to meet current and future EV demands. These studies conclude that if EVs are charged during off-peak load hours, new power plants will not be required to meet EV charging demand. If vehicles' charging is controlled and shifted to off-peak hours, EV charging will not increase the system peak load demand and therefore will not affect power generation adequacy. However, without controlled charging, large-scale EV deployment could decrease supply adequacy, and, therefore, will necessitate the construction of additional power plants. Specifically, [11] concludes that, depending on the time and place of the vehicle additions, EV charging could require additional power generation or increase the utilization of existing capacity and possibly reduce the reserve margins. In these cases, generation reliability would be a serious concern.

2) EV LOAD IMPACTS ON TRANSFORMER AGING

Large-scale EV deployment is likely to cause problems in the distribution system such as increased load demand, increased system losses, and additional voltage drops [10]–[28]. The increased load demand due to EV loads can overload service transformers, deteriorate the transformers' life, and increase system losses. Furthermore, EV charging can create new load peaks exceeding the service transformer's rated capacity, thereby accelerating equipment aging [12]–[14]. Specifically, [12] characterizes the impacts of EV charger harmonics on distribution transformer's life. The analysis portrays a quadratic relationship between the transformer's life and the total harmonic distortion (THD) of the battery charger current. For a reasonable transformer life expectancy, it is suggested that the current THD should not exceed 25-30%. Similarly, [13] evaluates the impacts of EV charging on transformer capacity overloading and concludes that a time-controlled EV charging can successfully mitigate transformer overloading concerns. A separate study concludes that, depending on the charging condition, EV charging can both positively or negatively affect transformer aging [3]. For example, an increased peak load demand may decrease transformer life expectancy. However, if EVs are primarily charged during off-peak hours, a flatter load profile could reduce the daily expansion and contraction of the transformer, resulting in a positive effect on transformer's life.

3) EV LOAD IMPACT ON DISTRIBUTION POWER QUALITY

EV charging is also likely to cause power quality problems in the distribution circuit including, but not limited to, under-voltage conditions, power unbalances, and voltage and current harmonics. As the number of EVs increase, so does the electricity demand required to charge their batteries. An EV load charged by a Level-2 charger can almost double the peak load demand of the homeowner [23]. The increased load demand due to EVs leads to additional voltage drops in the secondary service voltages, thus affecting the service voltage quality.

Several studies have been conducted to evaluate the impacts of EV charging on distribution voltages. The existing methods simulate multiple representative EV charging scenarios and project the potential impacts of EV charging using distribution circuit analysis tools. For example, [15] evaluates the impacts of the additional demand due to EV charging on system power losses and voltage deviations. To mitigate the effects of EV charging, the study recommends a controlled charging method. In [16], the impacts of quick EV charging on the power distribution system particularly on power system harmonics are evaluated and the maximum EV penetration level while avoiding serious harmonic impacts is determined. Furthermore, in [18], the impact of EV integration on power system loading and voltage profiles is evaluated and the benefits of several charging scenarios, such as dumb charging, timed charging, and controlled charging, on service voltage quality are quantified. Similarly, [19] investigates the effects of EV charging on distribution voltages, line drops, and system losses and [20] evaluates EV charging impacts on voltage limits, power quality, and power imbalance. In [21]–[24], several circuit parameters, both at local and global level affecting distribution voltages during EV charging are evaluated. Based on the analysis, it is concluded that that a large-scale EV deployment could violate recommended limits for secondary wire voltages and could cause voltage unbalance. Another study uses actual measurements and survey data to determine EV charging characteristics, including feeder load demand, EV charging starting time, battery state-of-charge (SOC), and proposes a stochastic approach to analyze the impacts of EV charging [26]. A Monte Carlo approach to evaluate the impacts of EV charging on feeder voltage quality, including under/over voltages and voltage imbalances, is proposed in [27]. Reference [28] presents a comparative analysis on the impacts of EV charging on typical NA and EU distribution circuits.

Since maintaining an appropriate voltage level for residential customers is of prime importance to utility companies, a detailed analysis of the impacts of EV charging on distribution voltages is required. In Sections III and IV, we present our approach to evaluating the voltage quality impacts of EV loads on residential customers. A short discussion on EV technologies and charging standards for both NA and EU distribution circuits is presented as well.

B. TIME-OF-USE (TOU) PRICING TO MITIGATE EV LOAD IMPACTS

The EV impacts analysis concludes that EV load charging during peak load hours can lead to undesirable grid impacts, such as an increase in the peak load demand and under-voltage conditions, thus necessitating grid expansions and upgrades. Several studies have concluded that uncontrolled charging of EV loads can limit the percentage penetration of EV loads into the distribution grid [10]–[28]. To avoid EV charging during peak load hours, utility companies deploy a TOU pricing structure. In a TOU scheme, the electricity usages are rated differently during peak and off-peak hours (lower rate), which motivates the customers to utilize the electricity generated during off-peak hours [30]–[32]. The schedule to begin peak and off-peak rates in a TOU scheme is referred to as a TOU schedule. In [32], the customer's response to time-varying rates for EV charging is investigated. The study aimed to understand the behavior and choices of EV customers to different EV tariff structures. The study concluded that EV customers were responsive to TOU prices and most of the EV owners programmed their vehicle to charge during the off-peak tariff periods. Therefore, TOU pricing can successfully stimulate EV charging during off-peak hours and flatten the load demand profile [30]–[32].

Implementing TOU pricing is a useful demand-side management scheme. However, if, while designing the TOU schedule, the total demand and load profile of the EV load is not taken into consideration, the effects of EV charging under a TOU schedule might get worse [33]–[35]. The reduced electricity rates during off-peak hours may result in simultaneous charging of multiple EV loads causing an even higher increase in peak load demand and thus larger additional voltage drops. To date, the implemented TOU schemes do not consider EV loads while setting up the TOU schedule. This calls for the development of an optimal TOU schedule that considers the EV load demand and thus minimizes the effects of EV load charging.

An optimized TOU schedule taking EV load demand into consideration is developed in [35]. The paper proposed an approach to minimize peak value and peak-valley difference of the feeder load demand. However, the proposed TOU structure in [35] does not take the convenience of EV owners into consideration. An optimal TOU schedule that benefits both utility companies and customers, while taking EV charging into consideration, is developed and presented in this paper [36]. The objective is to develop a practical approach for setting up a TOU schedule based on customer load demand, EV charging demand, and service transformer loading constraints. The selected time to begin off-peak rates in a TOU scheme should minimize the effects of EV charging on the secondary service voltages, while ensuring that EVs are fully charged by 7 am (worst case). Both grid and customer benefits can be simultaneously maximized in this way. The analysis suggests that the optimal time to begin off-peak rates is between 11 pm and 12 am [36].

C. SMART CHARGING ALGORITHMS TO MITIGATE EV LOAD IMPACTS

The TOU pricing structure, which aims to minimize EV loading during peak load hours by shifting the EV demand to off-peak hours, is not an optimal solution for significantly higher levels of EV penetration. Under TOU pricing, the simultaneous charging of several EV loads can create a second peak in load demand during off-peak hours [33]. The second peak will essentially limit the number of EVs that can be included in the distribution circuit. It should be noted that even after implementing TOU rates, a significant amount of power system capacity remains underutilized. This is because in the TOU pricing scenario all EV loads begin to charge simultaneously at the beginning of off-peak rates. The power system could be utilized more efficiently if the EV charging rate and charging start time are controlled to optimize a desired grid objective [37], [38]. The grid objective could include, but not be limited to, flattening the overall load shape profile, minimizing the charging cost, or minimizing power losses. Therefore, smart charging algorithms should be developed to accommodate higher percentages of EVs into the grid without causing negative impacts on the distribution feeders.

Given the potential benefits of the smart charging scheme, several articles [15], [39]–[55] have proposed algorithms to determine an EV schedule that can address a given grid objective. The objectives are primarily divided into two categories: maximizing benefits to utilities and maximizing benefits to EV owners.

1) CONTROLLED EV CHARGING – MAXIMIZE UTILITY BENEFITS

Several articles have addressed the first objective, i.e. maximizing utility benefits. To do so, the utility general installs an aggregator and decides the EV charging rates and charging start times in accordance with the current load demand or electricity generation cost. For example, Clement-Nyns *et al.* [15] proposed a coordinated charging scheme to minimize system power losses. The authors proposed a dynamic programming algorithm to determine the EV charging profiles for each EV load under both deterministic and stochastic settings. An EV charging strategy is proposed in [39] to minimize the peak load demand. In [39], both local and global control strategies based on quadratic programming are proposed to control EV load charging based on the local load information and overall global load information, respectively. Additionally, Sortomme et al. [40] established the relationship between feeder losses, load factor, and load variance and formulated several optimal charging algorithms to minimize the impact of EVs on the distribution system. In [41], a real time EV charging control strategy is proposed to minimize the total electricity generation cost and associated grid energy losses. Furthermore, [42] proposes a demand response strategy to decrease the potential impacts of new load peaks created by EV integration, while minimizing the cost of upgrading the infrastructure. Also, in [43] the authors propose a different demand response (DR) strategy to accommodate EV charging while keeping the peak demand unchanged, thus maximizing the grid usage. In [44], authors aim to flatten the total load demand and formulated the optimal EV charging scheduling problem as a discrete optimization problem. In [45] and [46], the optimal charging control for EVs is achieved by optimizing the energy usage of the distributed EVs for V2G frequency regulation services. In [47] a near real-time algorithm is proposed that takes into account the dynamic nature of EV charging demand. EV charging is formulated as a receding horizon optimization problem while taking the transformer and line capacity limits, phase unbalance, and voltage stability constraints into account [47].

Similarly, [48] proposes a receding-horizon optimization approach to obtain an EV charging schedule that also includes future EV penetration in the algorithm. After including future EV deployments, the authors claim their approach results in a flatter demand profile and better demand-side management.

2) CONTROLLED EV CHARGING – MAXIMIZE CUSTOMER BENEFITS

In a TOU/real-time electricity market, EV charging rate and time can be controlled to follow the TOU/real-time rate structure while minimizing the charging cost for EV owners. Several researchers have proposed to adjust the EV charging rates and charging start times according to the real-time electricity market. For instance, [49] introduces a control model for EV charging according to real-time electricity price information. In [50], a quadratic programming technique is used to optimize the charging-discharging process such that the charging cost is minimized while maximizing the discharging profit. A heuristic method is proposed in [51] to control the EV charging rate and time in response to the TOU pricing schedule. A real time V2G control algorithm with price uncertainty is proposed in [52] to maximize the profit of each EV owner. The profit includes the payment received by the EV owners from the utility company for selling power minus the cost of purchasing power from the grid. In [53], both global and local optimal EV control strategies are proposed to minimize the total cost of electricity that EV owners pay for EV charging. Similarly, [54] solves the EV charging schedule problem by simultaneously maximizing the aggregator's profits and minimizing the EV owner's costs. In [54], a linear programming based optimal control strategy is proposed for the static charging scenario, and a heuristic is developed for the dynamic charging scenario. In [55], the customer benefits are maximized by optimizing the local grid level constraints. The proposed EV charging strategy aims to deliver the maximum amount of energy to the EV loads while maintaining the circuit parameters (substation demand and feeder voltages) within the specified limits [55].

There are a few limitations to the smart charging algorithms designed to directly control the EV charging. For example, by scheduling EV charging rate and time to maximize utility benefits, the proposed algorithms ignore customer inconvenience. Additionally, many utilities do not implement real-time prices for their residential customers. Therefore, the optimal EV charging methods that maximize EV customers' charging benefits are inapplicable. In this paper, we propose a controlled charging algorithm aiming to minimize voltage variations during EV charging thus resulting in a flat voltage profile at each EV customer location. The proposed algorithm takes EV charging start and end time as a user input thus avoiding customer inconvenience and obtains an optimal EV charging schedule while minimizing the impacts of EV charging on feeder voltages.

III. ELECTRIC VEHICLE CHARGING TECHNOLOGY

This section presents a review of the current electric vehicle (EV) charging technologies. A brief discussion of different EV technologies including the types of EV batteries is presented, followed by a discussion on EV charging standards and EV charging levels for both NA and EU distribution circuits.

A. BACKGROUND OF ELECTRIC VEHICLE TECHNOLOGIES

Currently, three types of EV technologies are available on the market: hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs) [2], [25]. HEVs contain an internal combustion engine that runs on conventional liquid fuel but is also supplemented by an electric motor and onboard battery. PHEVs contain both an internal combustion engine and an electric motor and battery. The battery can be charged in three different ways: by plugging in, by the combustion engine, or by regenerative braking. BEVs also referred to as all-electric vehicles do not contain internal combustion engine. Instead, they use batteries to store electricity and run on the stored electricity [23].

Since HEVs do not require a separate charging infrastructure, this paper considers only PHEVs and BEVs. For the scope of this paper, PHEVs and BEVs are collectively referred to as EVs. EV batteries are quite different from the batteries used in consumer electronic devices such as laptops and cell phones. They should be light in weight and small in size and able to handle up to a hundred kW of power and high energy capacity (up to tens of kWh). Currently, two major battery technologies are used in EVs [23], nickel metal hydride (NiMH) and lithium ion (Li-ion).

B. ELECTRIC VEHICLE CHARGING STANDARDS

EV charging is either provided using a normal wall outlet or a dedicated charging circuit (e.g. wall box or charge pole). Usually EV charging is provided by a 120V (Level-1) or a 240V (Level-2) voltage supply (see Table 1) in North America and a 230V single-phase or 400V tri-phase in most other countries worldwide. The EV's charge couplers are described in IEC 62196 [58] and SAE J1772 [59]. For residential and public EV charging, the Type 1 coupler (SAE J1772 & IEC 62196 Type 1) is preferred in the U.S. and Japanese market. Type 2 (IEC 62196 Type 2) is preferred in the European market. Although the couplers are specified for up to 690 V AC and up to 250 A at 50 to 60 Hz, Level-1 (up to 16 A) and Level 2 (up to 32A) are most

TABLE 1. EV charging levels and charger specifications (NA standards).

Charging Level Type	Voltage Level	Power Level
Level-1	120 VAC	Up to 1.8 kW
Level-2	208-240 VAC	Up to 19.2 kW
Level-3 or DC Charging	480VDC	50 kW-150 kW

commonly implemented [28]. Fast charging circuits, for example, CHAdeMO and the Combined Charging System [60], usually deployed close to highways or on parking sites, are also becoming popular.

C. EV CHARGING - NORTH AMERICAN (NA) DISTRIBUTION CIRCUIT

The NA power system maintains its tri-phase characteristic down to the mid-voltage (MV) level. At the MV level, electric power is distributed to the low-voltage (LV) level through a pole-mounted transformer. On the LV side of the transformer, a single-phase three-wire supply provides power at 120V and 240V to each consumer, as shown in Fig. 1.

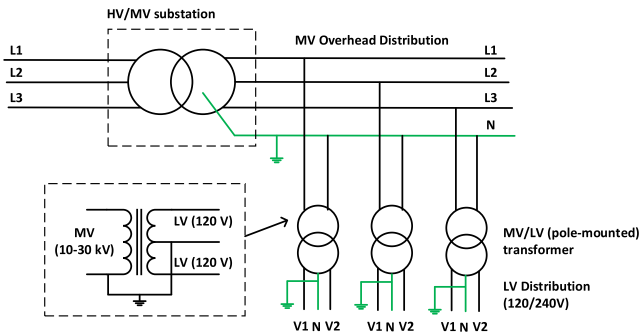

FIGURE 1. The structure of the North American power distribution system [28].

1) EV CHARGING MODES

The Society of Automotive Engineers (SAE) is responsible for the standardization of EV charging stations. SAE Surface Vehicle Recommended Practice J1772 (SAE J1772™) is the NA standard for EV electrical connectors. SAE identifies three charging levels (see Table 1) depending upon the energy transfer rate. Note that Level-1 and Level-2 chargers are deployed at residential facilities while Level-3 chargers are used at commercial charging stations. Fig. 2 shows the connection of EVs to the power distribution circuit for Level-1 and Level-2 charging.

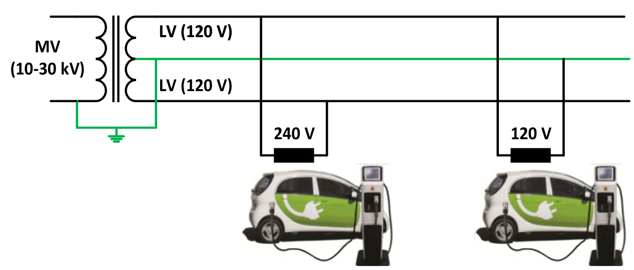

FIGURE 2. EV connection schemes in North America [28].

2) GRID REQUIREMENTS AND RESTRICTIONS IN NA

For a reliable power distribution, grid requirements and restrictions are imposed when connecting loads, such as EVs, to the distribution circuit. For the NA distribution system, ANSI C84.1-2011 [61] provides the national standard for voltage regulation. As per the standard, typically, the service voltage should range within ±5% of the nominal voltage rating and the three-phase voltage unbalance should not exceed 3%.

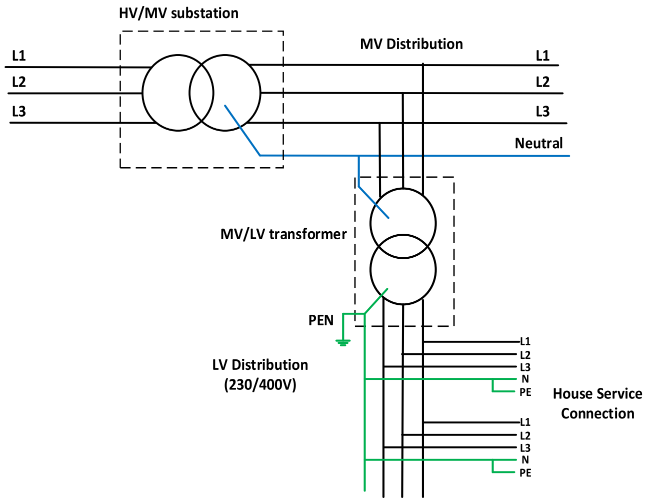

FIGURE 3. The structure of the European power distribution grid [28].

D. EV CHARGING - EUROPEAN (EU) DISTRIBUTION CIRCUIT

The EU distribution system maintains its tri-phase characteristic all the way to the house service connections. At the house service connection, the EU grid typically provides a TN-C-S system [28]. This system provides a tri-phase power supply with a separate neutral and earth. Fig. 3 shows the typical EU distribution circuit. The line-to-line voltage is 400V, and the line-to-neutral voltage is 230V.

1) EV CHARGING MODES

For single-phase EV charging, EV load is connected between one of the outer wires (L1, L2, or L3) and the neutral wire. The connection options for EVs are shown in Fig. 4. The maximum charging power for the single-phase charging is restricted to 4.6 kVA, 20 A on 230 V [28]. As for the tri-phase charging, the power limitation is 44 kVA, which

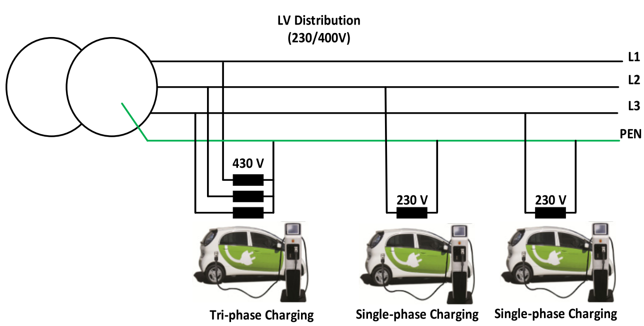

FIGURE 4. EV connection schemes in Europe [28].

TABLE 2. EV charging levels and charger specifications (EU standards).

Charging Level Type	Voltage Level	Power Level
Level-1	Single-Phase 230 V AC	Up to 4.6 kW
Level-2	Tri-phase 400 V AC	Up to 44 kW
Level-3 or DC Charging	480 V DC	50 kW-150 kW

equals 63A at 400V. Table 2 shows the charging levels for Europe, which are somewhat similar to the one from North America (see Table 1).

2) GRID REQUIREMENTS IN EUROPE

For Europe, and especially for Germany, grid restrictions and requirements are defined in EN 50160 [62]. The voltage should be within 90%-110% of the nominal voltage. The voltage asymmetry, defined as the ratio of the negative to positive sequence, should be smaller than 2%. Additionally, since single-phase charging may cause high neutral wire loading, the constant loading of the neutral wires should not exceed 60-70%.

IV. UNDERSTANDING THE IMPACTS OF EV CHARGING ON DISTRIBUTION VOLTAGES

In this section, a systematic approach is presented to evaluate the effects of EV loads at both the local and global secondary circuit level. The analysis is conducted for residential customers using Level-2 battery chargers for their EVs. The detailed EV integration study is conducted for a typical NA residential distribution circuit and a typical tri-phase EU distribution circuit. Additionally, a comparison between the EV charging impacts on NA and EU distribution circuits is also presented.

The local circuit analysis portrays the effects of EV load charging at the local distribution circuit level. The objective is to evaluate several distribution circuit parameters that can potentially affect the distribution circuit voltage quality. Using this analysis, utility companies can determine potential conditions leading to poor voltage quality, and can then take specific steps towards mitigating the impacts of EV charging for the most susceptible customers.

The global circuit analysis assesses the effects of EV charging on the entire distribution circuit. This analysis helps in planning, expanding, and forming strategic policies for EV charging within the distribution circuit. For example, based on the identified most affected areas, utilities can find out an optimal location to deploy distributed energy storage units or distributed generation plants for mitigating the EV charging impacts.

In the following section, we first summarize our analysis approach by describing the distribution circuit, customer load, and EV load models. Next, we present the parameters for the local and global circuit analyses, followed by the results and discussions. The EV charging impacts are also evaluated for a typical EU distribution circuit. Finally, the impacts of EV charging on NA and EU distribution circuits are compared. While the NA circuit is most impacted by service voltages and short-circuit (SC) capacities, the EU tri-phase circuit is primarily affected by single-phase and concentrated EV load charging.

A. ANALYSIS APPROACH

A typical real-world 13.8-kV NA radial distribution is selected for the analysis [63]. The three-phase steady-state load flow model includes a complete electrical model of the distribution circuit including the substation transformer, three-phase primary wires, laterals, secondary circuits, service transformers, and individual customer loads. For each customer load, a 24-hour load shape profile is generated and assigned according to the stratified billing rates and the load demand data measured at the substation. These EV loads are modeled as a constant power load with an associated load shape. Finally, a 24-hour EV load profile is generated based on the type of EV charger and EV battery.

Specifically, the study presented herein is carried out for Level-2 EV chargers with power ratings of 3.84-kW (240V/16A) and charging efficiencies of 90% charging a 16-kWh EV battery. In order to evaluate the impact of EV loads on the distribution voltages, a three-phase load flow analysis is performed for one day at every 15-minutes. The analysis considers the load shape profiles of both EV and conventional loads. The section below describes the evaluation conditions in detail.

1) DISTRIBUTION CIRCUIT MODEL

A typical real-world 13.8-kV radial distribution circuit serving predominantly 120/240V single-phase three-wire residential loads is selected (see Fig. 5) for the analysis. The selected distribution circuit has approximately 7,000 buses and supplies 1,473 secondary customers, where a majority

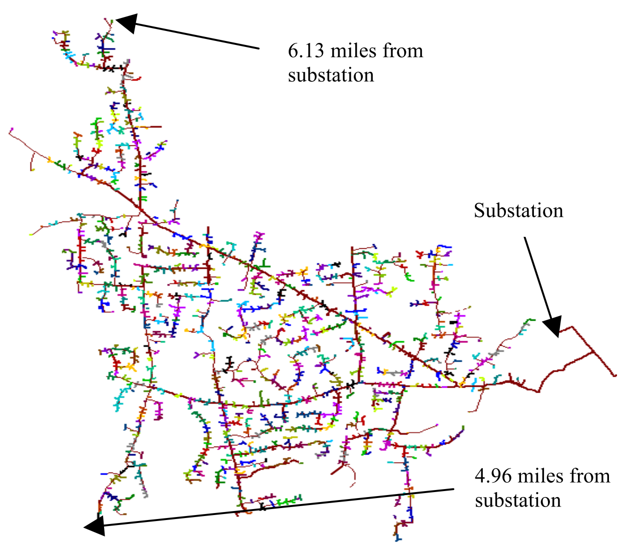

FIGURE 5. One line diagram of the selected residential distribution circuit.

of the customer loads are single-phase. The farthest load is located 6.13 miles from the substation. The peak load demand recorded at the substation is 7.77 MW. The load demands at the individual customer locations are determined by running a load allocation algorithm using customer consumption data, connected kVA information, and measured load demand at the substation [22].

2) CUSTOMER LOAD MODEL

To evaluate the effects of EV charging on the distribution circuit, the load flow analysis must be conducted for at least a day. The 24-hour analysis requires the daily load shape profiles of the conventional loads. In this study, the hourly kW consumption data for each 'stratified load type' and the monthly kWh demand for each customer load is used to generate and assign an approximate daily load shape profile to each customer load.

Utilities provide electricity in several different pricing tiers that are stratified according to the range of monthly kWh usage. This is referred to as 'stratified pricing data'. The loads served at different pricing tiers are referred to as 'stratified load types'. The daily load shape profile for each conventional load is generated using the kWh consumption data for each 'stratified load type', the stratified pricing data, and the monthly kWh demand measured for each load. First, a daily load shape profile is generated for each 'stratified load type' by averaging hourly load demand measured at the substation over the year. Next, the monthly kWh demand and 'stratified pricing data' is used to assign an appropriate load profile to each conventional load. Details of the simulation can be found in [22].

3) EV LOAD MODEL

In this study, EV loads are modeled as a constant power load. For voltage quality evaluations, the daily load shape profile for the EV load is also required. Therefore, based on the type of EV battery and the type of EV charger, the load shape profile for the EV load is generated.

A daily load shape profile for a 16 kWh EV load with 20% SOC, charged by a 240V-16A Level-2 EV charger connected to a residential facility, is developed and shown in Fig. 6. The EV load shape profile is developed using the constant power load characteristic and a fixed EV starting time. To simulate the worst case scenario, the EV demand is assumed to overlap with the peak demand hours of the residential service transformer, i.e. 6 to 10 pm. The EV model details can be found in [23].

B. EV LOAD IMPACTS USING LOCAL CIRCUIT ANALYSIS

The effects of EV charging at the local circuit level are evaluated in this section. The objective is to understand the factors at the local circuit level that may affect the distribution circuit voltages due to EV load charging. For this analysis, a 120/240V secondary circuit is selected, which is supplied by a 50-kVA service transformer and connected to eight residential loads with a total peak load demand of 36.6 kW.

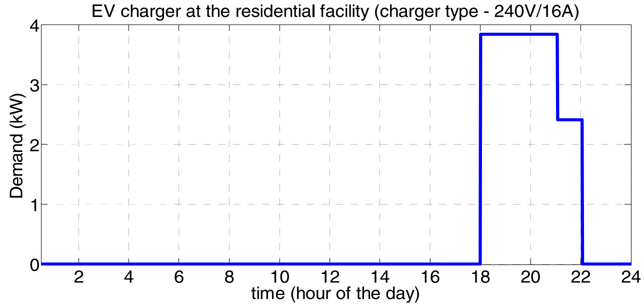

FIGURE 6. An example EV load shape profile for EV load located at a residential facility. EV charger - 240V/16A (3.84 kW)-16-kWh battery.

The EV loads are populated according to the conditions specified for each charging scenario under evaluation. Additional voltage drops in the primary and secondary wires due to EV load charging are recorded. Several factors evaluated in this section are as follows:

1. The relative location of the service transformer with respect to the substation;
2. The relative location of the EV load with respect to the service transformer;
3. The size of EV charger (240V/16A or 240V/30A) and the effect of adding an EV adjacent to an existing EV.

1) LOCATION OF SERVICE TRANSFORMER SUPPLYING FOR EV

This section evaluates how the service transformer's location relative to the substation impacts the distribution circuit voltages during EV load charging. The one-line diagram for the secondary service under evaluation is shown in Fig. 7. Four 240V/16A (3.84-kW) EV loads, which correspond to approximately 50% of the conventional residential loads, are connected to the secondary circuit. Voltage profiles at the primary service transformer (13.8-kV side) and at each load node in the secondary wire, with and without EV loads, are recorded. To keep the comparison unbiased to topological changes, an identical service transformer and a secondary circuit are placed close to the substation and the analysis is repeated.

Table 3 summarizes the effects of EV charging on the primary and secondary wire voltages for both locations of

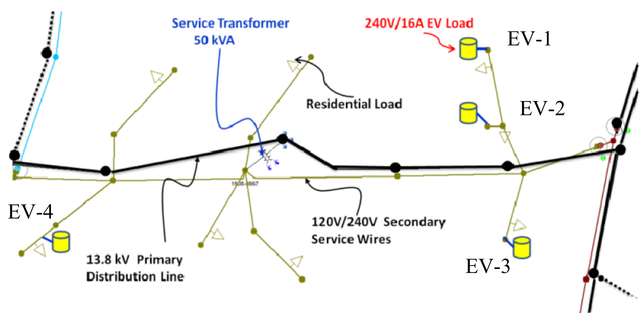

FIGURE 7. One line diagram for the 120V/240V secondary distribution circuit.

TABLE 3. Effects of location of the service transformer on primary and secondary service voltages.

Observations drawn from the study	At primary of the service transformer		At the farthest load node in secondary	
	Service transformer is		Service transformer is	
	Remote	*Nearby*	*Remote*	*Nearby*
SC capacity (MVA)	24.39	139.01	0.174	0.178
Add'l voltage drop due to 4 EVs	0.13%	0.023%	4.41%	4.32%
Add'l voltage drop due to 1 EV	0.034%	0.006%	1.40%	1.38%
Add'l voltage drop of 1 %	62 EVs per phase	520 EVs per phase	0 EV	0 EV

the service transformer. The largest additional voltage drops associated with EV load charging are about 0.13% for remote service transformers and about 0.023% for nearby service transformers. Due to a high short-circuit (SC) strength at both transformer locations, the primary voltages do not drop significantly due to EV load charging. Although, for both locations, the primary wires record small voltage drops, their values differ significantly in the absolute terms. The result is attributed to the higher short-circuit capacity at the primary of the nearby service transformer.

For secondary service voltages, the biggest effect of EV charging is on the load node farthest from the service transformer. The largest additional voltage drops for the remote and nearby secondary circuits are 4.41% and 4.32%, respectively. Lower short-circuit capacity leads to larger additional voltage drops in the secondary service voltages. Also, a comparable short-circuit capacity at the load node for both secondary services (remote and nearby) results in an approximately equal additional voltage drop (about 4.5%) during EV charging.

2) LOCATION OF EV CHARGERS

In this section, the impact of the location of the EV chargers within the secondary service is evaluated. The same 120/240V secondary circuit (Fig. 7) remote from the substation transformer is selected for the analysis. One 240V/16A (3.84 kW) EV load is connected at the farthest load node from the service transformer as shown in Fig. 8 and the three-phase load flow analysis is simulated for a day. The EV load is then moved to the load node closest to the service transformer and the same analysis is repeated (see Fig. 9).

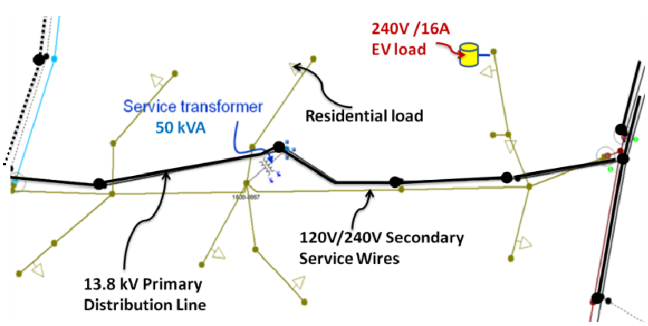

FIGURE 8. Secondary circuit with EV load remote from the service transformer.

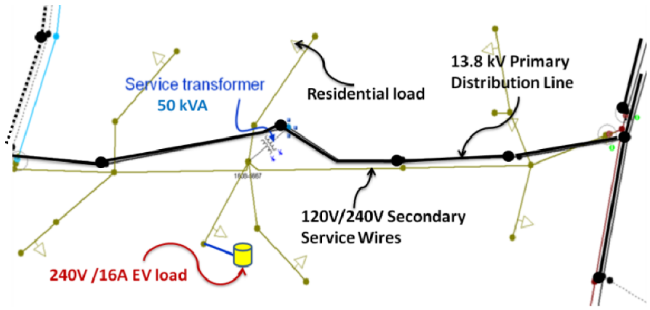

FIGURE 9. Secondary circuit with EV load nearby the service transformer.

The service voltages recorded at the EV load node are compared for both EV load locations (see Table 4). The largest additional voltage drops due to EV load charging when deployed at the remote and nearby load nodes are 1.7% and 0.81%, respectively. A lower short-circuit capacity at the farthest load node results in larger additional voltage drops in the secondary service voltages.

TABLE 4. Effects of location of EV load on secondary wire voltages.

EV is at the load node	SC capacity at the load with EV (kVA)	Largest Add'l voltage drop due to 1 EV load
Remote from the service transformer	174 kVA	1.7 %
Nearby the service transformer	393 kVA	0.81 %

3) EFFECTS OF EV LOAD SIZE AND ADDITIONAL EV LOAD

The effects of the size of the EV charging station and additional EV load on the voltage profile of the secondary circuit are evaluated and compared in this section. The same secondary circuit remote from the substation (see Fig. 7) is chosen for the study and is populated with an EV load at the farthest load node. Two charging scenarios are simulated to evaluate the effect of EV load size, one with a 240V/16A EV charger and the other with a 240V/30A EV charger both charging a 16-kWh EV battery. The largest additional voltage drops recorded at the load node populated with EV load for a 16A and a 30A EV charger are approximately 1.7% and 3.24%, respectively. As expected, the largest voltage drop increases when the size of the EV charger is increased. Next, the potential impacts of adding an additional EV load are evaluated. An EV load is added at the farthest load node from the service transformer. An additional EV load is added adjacent to the existing EV load. On deploying the additional EV load, the largest additional voltage drop in the secondary circuit increases from 1.7% to 3.2%.

C. EFFECT AT GLOBAL CIRCUIT LEVEL

This section aims to understand the EV load impacts at the global circuit level. Specifically, the analysis aims to identify the impacts of increasing EV penetration and EV load clustering on the distribution circuit voltages. Depending upon the projected EV penetration level, this analysis can be used by utilities in planning mitigation actions at the global circuit level. For example, depending upon the locations projected to be most affected by EV charging, an optimal location to deploy distributed energy storage units or distributed generation plants to mitigate EV charging concerns can be determined.

1) EFFECT OF INCREASING EV PENETRATION

The objective of the study is to identify the effects of increasing EV load penetration on primary and secondary service voltages. The study helps in identifying the worst case conditions and potential secondary service locations that will suffer serious voltage drops due to EV charging. First, each single-phase secondary service supplied by the residential distribution circuit is loaded with one EV load (a total of 669 EV loads) and the additional voltage drop at the primary of each service transformer is recorded. Then, the number of EV loads at each secondary service is increased to two, three, and four, amounting to a total of 1,138, 2,007, and 2,676 EV loads, respectively, in the distribution circuit. A plot of the load demand, with and without EV loads, recorded at the substation transformer is shown in Fig. 10.

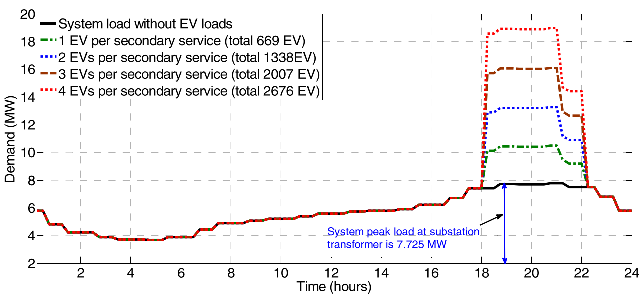

FIGURE 10. Hourly load demand profile, with and without EV loads, measured at the substation.

TABLE 5. Effects of EV loading on the primary wire voltages.

Effect of loading each secondary service in the distribution circuit with EV loads. The total number of secondary services are 669.				
Number of EV	*Additional EV loading (%)*	*Largest additional voltage drop*	*Mean value*	*Standard deviation*
669	35.27%	1.35%	0.95%	0.24%
1338	71.13%	2.77%	1.95%	0.51%
2007	107.77%	4.25%	3.04%	0.80%
2676	144.92%	5.7%	4.19%	1.09 %

Table 5 summarizes the largest additional voltage drops recorded at the primary wires corresponding to different percentages of EV penetration. On increasing EV penetration, the largest additional voltage drop at the primary wire increases. The distribution of the additional voltage drop across the feeder can be approximated using a Gaussian curve. This means that very high and very low voltage drops are recorded for fewer feeders. The service transformers farther away from the substation and away from the main primary feeders observe relatively higher additional voltage drops at their primary wires. The detailed analysis can be found in [24].

Due to additional voltage drops in the secondary service wires, an even higher voltage drop is recorded at the secondary customer locations supplying for EV loads. On increasing EV penetration, the additional drop in primary wire voltages may remain small, but for secondary wires, especially the ones that are remote from the substation and are longer in length, the additional voltage drop could shoot to alarming levels [24]. In conclusion, the secondary services farther away from the substation are more susceptible to voltage drop problems due to EV loads. Furthermore, the study concludes that the largest additional voltage drop increases as the distance of customers (connected to EV) from the service transformer increases. Therefore, a longer secondary network with a lower short circuit capacity raises additional concerns regarding the voltage drop issues due to EV loads charging.

2) EFFECT OF EV LOAD CLUSTERING

In this section, the effects of clustering EV loads on the distribution circuit are evaluated. A primary lateral far away from the substation is selected for the analysis. The selected primary lateral serves 22 secondary service transformers. Each secondary service served by the primary lateral is loaded with one EV load and the largest additional voltage drops at the primary of the secondary services are recorded. The locations of the primary wire and secondary services selected for the analysis are shown in Fig. 11.

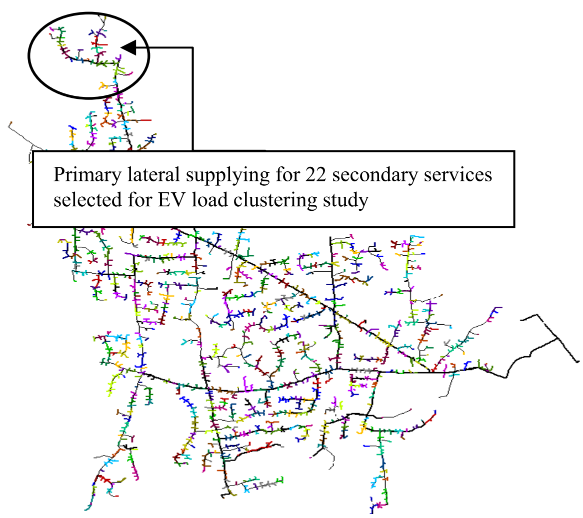

FIGURE 11. Secondary services deployed with EV loads for clustering analysis.

The number of EV loads per secondary service is varied from 2 to 4, amounting to a total of 44, 66, and 88 EV loads for the distribution circuit. It has been found that the primary laterals supplying EV loads experience higher voltage drops when EVs are charging. The largest additional voltage drop recorded at the primary wire on loading the selected secondary services with one EV load each (22 EV loads total) is 36.36 V (0.43%). An important observation from this case study is the unbalance in three-phase power demand due to EV load clustering. As a result of unbalanced load demand, several primary terminals of service transformer record an increase in supply voltage. The increase in primary wire voltage is as high as 0.22% on loading selected secondary services with 1 EV load each. Table 6 summarizes the effects of EV load clustering on the primary wire voltage.

TABLE 6. Effects of EV load clustering on the primary wire voltages.

Effects of EV load clustering on primary wire voltages Number of secondary services = 22			
Total number of EV loads	**Additional loading due to EV load (%)**	**Largest additional voltage drop**	**Largest increase in service voltage**
22	1.16%	0.45%	0.22%
44	2.33%	0.88%	0.45%
66	3.52%	1.35%	0.68%
88	4.75%	1.81%	0.91%

As for the secondary service voltages, due to EV load clustering, a few secondary services record a drop while others record an increase in the supply voltage. The secondary services loaded with EV loads in this case study are primarily supplied by Phase A or Phase B of the primary supply. Due to EV loading, voltage drops in the secondary services served by Phase A and Phase B of the primary wire are recorded. The secondary services supplied by Phase C of the primary wire, however, record an increase in the supply voltage. Please refer to [24] for detailed analysis.

D. EV LOAD IMPACTS ON THE EUROPEAN DISTRIBUTION CIRCUIT

This section presents the approach and results of the EV integration study conducted for a typical EU distribution circuit in urban and suburban areas. A typical real-world 400V distribution circuit serving tri-phase residential loads is selected for the study. The EV charging impacts are evaluated using the following two scenarios: one with the clustered EV charging at a parking lot and the other with distributed EV charging along the street sides [28].

1) DISTRIBUTION CIRCUIT MODEL

The study is conducted using a real world low-voltage 400V tri-phase distribution circuit serving predominantly 230V single-phase and 400V tri-phase residential loads and spanning approximately 2 km in length (Fig. 12) [28]. The circuit is supplied by a standard three-phase 630 kVA, 10-kV/0.4-kV transformer. The circuit supplies 25 houses (H1) with 3-kVA

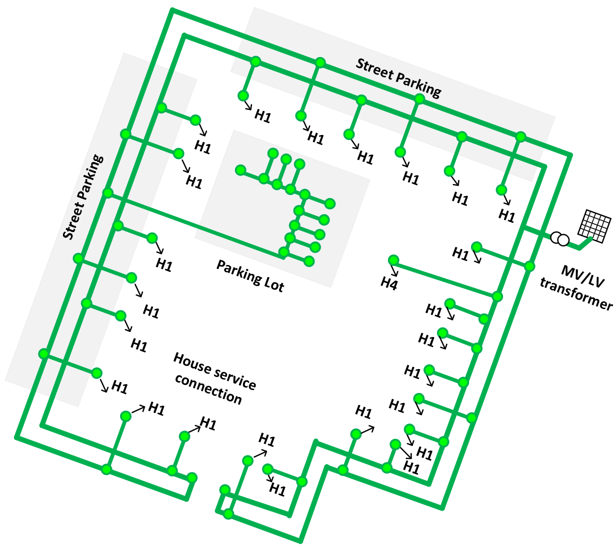

FIGURE 12. Typical European low-voltage distribution circuit [28].

and one house (H4) with a 12-kVA balanced load demand. A balanced preloading condition is used to understand the impact of single-phase EV charging. In this case, the transformer is symmetrically loaded with 38% of its capacity. As discussed before, two EV charging scenarios are simulated. The first scenario evaluates the concentrated EV charging impacts and the second scenario analyzes the impacts of distributed EV charging. In both cases, 10 EVs are placed in the distribution circuit [28].

2) IMPACTS OF CONCENTRATED EV CHARGING ON A PARKING LOT

In this scenario, 10 EVs are placed on a parking lot, as shown in Fig. 13. The EVs are connected to Phase L1 and

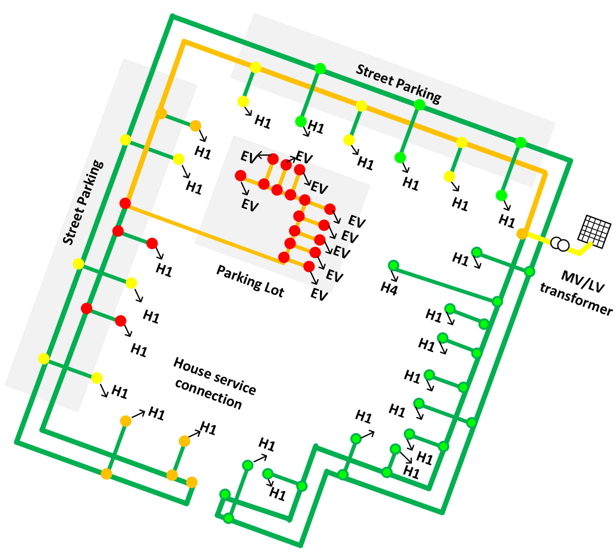

FIGURE 13. Distribution circuit loading for the clustered EV charging scenario.

are assumed to be charging simultaneously using 4.6-kVA chargers. Note that in order to account for the uncertainty of the actual selected EV charging phase, all EVs are placed on one of the phases (L1). Fig. 13 portrays the results of the simulation in a color map. The line color represents the loading of the wires. For example, the most loaded wires are shown in orange, followed by yellow and green. The node colors represent the severity of the voltage drop, with the highest voltage drops in red, followed by orange, yellow, and green.

The node voltages at each load node, including the node supplying for the parking lot, are recorded. During EV charging, the voltages on Phase L1 decreases towards the node supplying for the parking lot, while the voltages increase on Phase L2. The selected distribution circuit is close to violating the acceptable voltage limit when 10 EVs are connected on the same phase. The voltage asymmetry also increases and reaches 2%, which is higher than the acceptable limit [28].

3) IMPACTS OF DISTRIBUTED EV CHARGING ON A STREET

In this second scenario, 10 EVs are charged simultaneously on the two street sides, as shown in Fig. 14. Similar to the previous scenario, each vehicle is charging at 4.6 kVA single-phase on phase L1. In this case, all voltages are within the acceptable range, and the voltage asymmetry ranges between 0.5 and 0.9% [28]. The simulated scenario does not portray node voltage or voltage asymmetry limit violations caused by EV charging. Also, the distribution circuit can accommodate additional EVs in the distributed EV deployment case.

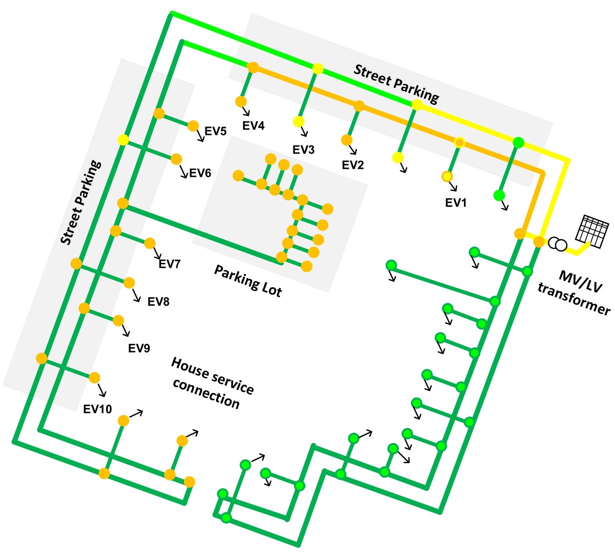

FIGURE 14. Distribution circuit loading for the distributed EV charging scenario.

The study on the EU distribution circuit reveals that increasing the amount of EVs will impact the grid. The major impact, however, is due to the clustering of EVs at one house service connection and due to single-phase EV charging.

E. COMPARISON OF EV CHARGING IMPACTS ON NA AND EU DISTRIBUTION CIRCUITS

A detailed comparison of the impacts of residential EV charging on a typical NA and EU distribution circuit is presented in [28]. As for the NA distribution circuit, the EV charging analysis concludes that residential EVs are likely to affect secondary circuit voltages more than the primary wires. The NA distribution circuit is primarily affected by the short-circuit capacity at the nodes, while the tri-phase EU distribution circuit observes the major impact due to EV load clustering and single-phase EV charging resulting in voltage asymmetry.

For a NA distribution circuit, it is observed that the location of secondary service with respect to the substation transformer does not affect the additional voltage drop observed due to EV load charging. However, an EV load located closer to the service transformer results in a lower additional voltage drop as compared to one located farther from the service transformer. Additionally, due to a lower short-circuit capacity at the secondary load nodes, a higher EV load penetration affects the secondary wires more than the primary wires. EV load clustering causes load demand unbalance and results in an increase in the voltages at a few secondary service locations, thereby increasing the voltage asymmetry.

As for the EU distribution circuit, the major impacts of EV charging are caused by EV clustering at one load node and, also, single-phase EV charging. The single-phase charging causes asymmetries on the low-voltage distribution circuit thus potentially leading to a violation of grid requirements because of asymmetry, under-voltage, or neutral wire loading. In sum, clustering of EVs at one service connection worsens the EV charging impacts and leads to a quicker violation of the voltage or current based grid operational limits.

V. INFRASTRUCTURAL UPGRADES TO MITIGATE EV LOAD IMPACTS

In the previous section EV charging was shown to considerably affect the secondary service voltages and the service transformer load demands. This calls for the evaluation of effective mitigation actions addressing the effects of EV charging. This section evaluates the mitigation of EV charging impacts by upgrading the distribution system infrastructure. The mitigation schemes evaluated include increasing the kVA rating of the service transformer and reconfiguring the secondary circuit with an additional service transformer. The analysis is conducted using the 13.8-kV residential distribution circuit shown in Fig. 5. The impact of EV charging on feeder voltages before and after implementing the mitigation schemes is compared.

Although increasing the kVA rating of the service transformer mitigates the transformer load demand concerns, doing so does not significantly decrease the feeder voltage drops. However, the largest additional voltage drop caused by EV charging does decrease significantly when the secondary circuit is reconfigured with an additional service transformer.

Adding a service transformer and reconfiguring the secondary circuit, however, requires additional infrastructural expenses.

A. INCREASING THE SIZE OF SERVICE TRANSFORMER

This section evaluates if increasing the kVA rating of the service transformer can mitigate the impact of EV charging on voltage quality. A 37-kVA service transformer remote from the substation is selected for the study. The secondary circuit under evaluation is assigned one 240V/16A EV charger at the farthest load node from the service transformer charging a 16-kWh EV battery. The kVA rating of the transformer is then increased to 75 kVA, and the largest additional voltage drop is recorded while the EV load is charging. The additional voltage drops for both service transformer ratings are compared in Table 7.

TABLE 7. Effects of the kVA rating of the service transformer on voltage drop.

Load nodes in the secondary circuit	Largest additional voltage drop recorded when the kVA rating of the transformer is	
	37 kVA	75 kVA
Load node with EV load	2.06 V (1.7%)	1.98 V (1.64%)
Load nodes without EV, but in EV charging path	1.76 V (1.45%)	1.68 V (1.38%)
Other load nodes	0.17 V (0.13%)	0.1 V (0.084%)

On increasing the kVA rating of the service transformer to twice its nominal rating, an insignificant decrease in the largest additional voltage drop is recorded—only 0.06%. Therefore, increasing the service transformers kVA rating does not adequately mitigate the voltage drop concerns.

An additional case study is carried out with a secondary circuit supplied by a 50-kVA service transformer. The secondary circuit is populated with four 240V/16A EV loads, and the kVA rating of the service transformer is increased to three times its nominal value in steps of 10 kVA. The largest additional voltage drops recorded in the secondary circuit are plotted against the kVA rating of the service transformer as shown in Fig. 15.

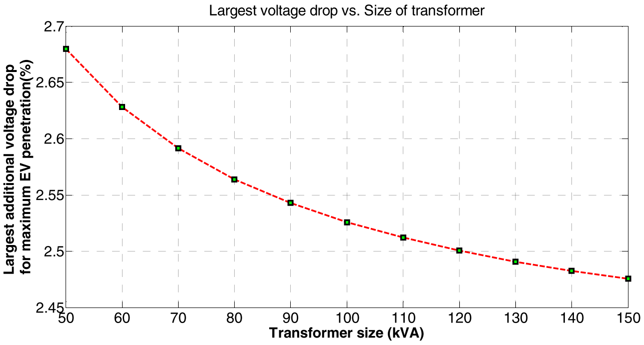

FIGURE 15. Largest additional voltage drops vs. the size of the service transformer.

It is evident from Fig. 15 that the largest additional voltage drop decreases from 2.68% to 2.47% on increasing kVA rating of the service transformer to thrice its nominal value. In conclusion, increasing the kVA rating of the service transformer can mitigate the load demand concerns, but it is an inefficient method for mitigating the EV load voltage drop concerns.

B. SPLITTING AND RECONFIGURING THE SECONDARY CIRCUIT USING AN ADDITIONAL SERVICE TRANSFORMER

The effects of reconfiguring the secondary circuit by adding an additional service transformer in mitigating the secondary circuit voltage drop concerns are evaluated in this section. A 50-kVA service transformer supplying five secondary loads is selected for the study (Fig. 16). The circuit is loaded with four EV loads and the largest additional voltage drop due to EV load charging is recorded. This is referred to as the base case in the following discussion.

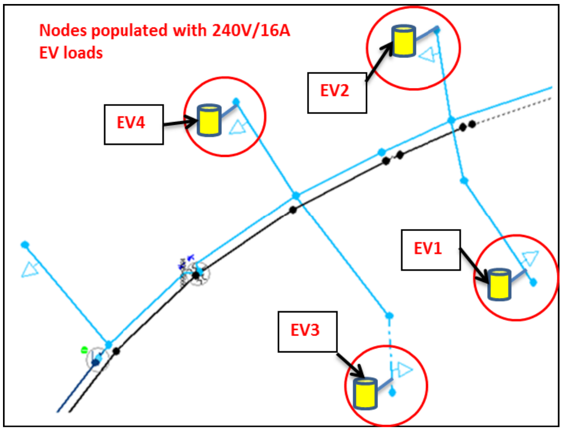

FIGURE 16. The secondary circuit selected for the evaluation of the circuit reconfiguration and the locations of EV loads.

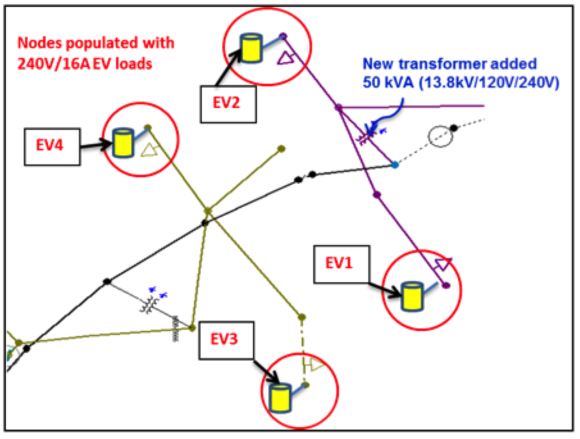

FIGURE 17. The secondary circuit is split into two circuits using an additional 50-kVA service transformer.

An additional 50-kVA service transformer is added to split the secondary circuit into two circuits, as shown in Fig. 17.

The original transformer now supplies two loads, the new transformer supplies the remaining three loads, and each service transformer supplies two EV loads. The voltage profile with and without the EV loads (at the load node) is recorded and compared to the base case. In order to validate further that the size of the transformer does not play a significant role in mitigating secondary circuit voltage problems, an additional case is simulated. The kVA rating of both transformers is decreased to 25-kVA, making their sum 50 kVA. The additional voltage drop in the secondary circuit is recorded with and without EV loads, with the same arrangement of EV loads as in the base case. The results are summarized in Table 8.

TABLE 8. Effects of reconfiguring the secondary circuit using an additional service transformer.

EV load node	Largest additional voltage drop in the secondary circuit		
	Base case circuit	*Splitting the circuit into two using*	
		50 kVA + 50 kVA transformers	*25 kVA + 25 kVA transformers*
EV 1	3.2 V (2.61 %)	0.46 V (0.37 %)	0.62 V (0.49%)
EV 2	3.29 V (2.68 %)	0.54 V (0.43 %)	0.69 V (0.55 %)
EV 3	2.77 V (2.55 %)	1.77 V (1.57 %)	1.93 V (1.27%)
EV 4	2.32 V (1.88 %)	1.34 V (1.08 %)	1.51 V (1.21%)

Splitting and reconfiguring the secondary circuit with an additional service transformer significantly decreases the additional voltage drops caused by EV load charging. However, the degree to which the secondary circuit's voltage drops are mitigated depends on the location of the additional service transformer. For example, voltage drop concerns are decreased more when the additional transformer is placed closer to the new secondary circuit. Unfortunately, because it requires an additional service transformer, this method is expensive in terms of effort and cost.

VI. TIME-OF-USE (TOU) PRICING TO MITIGATE EV LOAD IMPACTS

The infrastructural upgrades implemented to mitigate EV load concerns, such as resizing/adding a service transformer and reconfiguring the secondary circuit, require significant efforts and cost. To avoid any unnecessary cost, utilities implement a TOU pricing structure. TOU pricing encourages EV owners to charge their EVs during off-peak hours. The result is a flattened load demand profile and a reduction in additional voltage drops caused by EV charging [30], [31].

A few studies have projected that if the off-peak rates in a TOU schedule are not set to an optimal time, the effects of EV charging can get worse [33]–[35]. This is because reduced electricity prices during off-peak hours will encourage EV owners to simultaneously charge multiple EVs. In turn, an even higher increase in load demand and larger additional voltage drops could result at the beginning of off-peak hours. To date, utility companies do not consider EV loads while setting up the TOU schedule. This calls for the development of an optimal TOU schedule that considers the EV load demand and thus minimizes the effects of EV load charging.

In this section, we develop a practical method to set up an optimal TOU schedule that benefits both the utility and the customers while taking EV charging into consideration. The aim is to determine the time to begin off-peak rates in a TOU schedule so that the largest additional voltage drops and substation peak load demand are decreased and EVs are fully charged by 7 am, so as to avoid inconveniencing customers. A summary of our evaluation approach and results are discussed in this section. Please refer to [36] for the detailed approach and results.

A. ANALYSIS APPROACH

The general evaluation procedure is as follows: A 50-kVA service transformer remote from the substation is selected for the analysis. The secondary circuit supplied by the transformer is loaded with four EV loads. The analysis is performed for a 240V/16A Level-2 EV charger, with 20% SOC of the incoming vehicle. The EV load profile is specified by the charging scenario under evaluation. Various charging scenarios considered in this section, and their evaluation parameters, are summarized in Table 9 [36]. The charging scenarios specified in Table 9 are simulated for both a 24-kWh (Nissan Leaf [64]) and a 16-kWh (Chevy Volt [65]) EV battery load.

TABLE 9. Various charging scenarios simulated for both 24-kWh and 16-kWh EV battery loads charged using a 240V/16A EV charger.

Charging scenario	Probability Density Function (PDF) for EV charging starting time	Number of Monte Carlo runs
Unscheduled charging	Gaussian distribution with mean = 8 pm, standard deviation = 2 hours	100 runs
Simultaneous charging at 8 pm, 10 pm, 11 pm, 12 am, 1 am, 2 am, and 3 am	No PDF, all EVs start charging at the same time	Not required
Randomized charging at 8 pm, 10 pm, 11 pm, 12 am, 1 am, 2 am, and 3 am	Positive half of Gaussian distribution with mean = time of the controlled charging, standard deviation = 30 min	100 runs

In the unscheduled charging scenario, we assume that the utilities do not implement TOU pricing. Therefore, under this scenario, residential customers do not program or schedule the starting time for EV charging. To understand the effect of this charging scenario, multiple Monte Carlo runs are simulated by randomizing the EV chargers' starting times, and system peak load demand and additional voltage drops are recorded. The EV starting time is assumed to follow a Gaussian distribution with the mean charging time at 8 pm and a standard deviation of 2 hours [36]. As mentioned in Table 9, 100 runs are simulated, and the results recorded for each run are averaged to obtain an average voltage and load shape profile for the unscheduled charging scenario.

The time-controlled charging scenarios with simultaneous EV load start times are simulated for different hours. The EV charging start time is varied between 8 pm and 3 am and all EVs are assumed to begin charging simultaneously at that hour. This case represents the scenario when all EV owners have programmed their vehicles to begin charging immediately at the time when the off-peak rates begin. The largest increase in load demand and the largest additional voltage drop for each case is recorded individually and compared. To make the analysis of time-controlled charging of EV loads more general, randomness is added to the EV charger start time, indicating most owners program their EVs to begin charging at the beginning of off-peak rates, with a few exceptions. The randomness is represented by the positive half of a Gaussian distribution, with mean at the time when controlled charging begins and the standard deviation equal to 30 minutes [36]. Multiple cases are simulated by shifting the EV charger start time to different hours of the day, ranging from 8 pm to 3 am. For each hour, multiple Monte Carlo runs are simulated by randomizing the EV chargers' start times within that hour. The load flow results corresponding to each run are averaged to obtain the voltage profile and load shape profile for each hour under analysis.

B. TIME-CONTROLLED CHARGING OF 24-kWh AND 16-kWh EV LOADS USING A 240V/16A CHARGER

In this section, the time-controlled charging scenario simulation results, for both 24-kWh and 16-kWh EV loads, are summarized. The secondary circuit is populated with four 240V/16A EV chargers, each charging either a 24-kWh or a 16-kWh EV load, depending upon the charging scenario.

For both 24-kWh and 16-kWh EV loads, multiple simultaneous and randomized charging scenarios are simulated. The EV charging start time ranges between 8 pm and 3 am. As the EV charging is shifted to off-peak load hours (any time after 8 pm), peak load demand attributable to EV charging decreases. A second peak in load demand occurs when EV charging start time is shifted to any time after midnight. The second peak recorded for any of the time-controlled charging scenarios is not as significant as the one observed due to the unscheduled EV charging scenario. As for the largest additional voltage drops, as the start time of EV charging is shifted from 8 pm to 3 am, the largest additional voltage drop decreases [36].

C. OPTIMAL TIME TO BEGIN OFF-PEAK RATES IN A TOU SCHEME

The analysis suggests that the optimal time to begin off-peak rates in a TOU pricing scenario is between 11 pm and 12 am (midnight) [36]. Note that a 24-kWh EV load requires around 6 hours 30 minutes to fully charge, while a 16-kWh EV load takes 4 hours to fully charge from a 20% state of charge (SOC) using a 240V/16A charger. The off-peak rates should begin during a time when the effects of EV charging on the secondary service voltages and load demands can be minimized while also ensuring EVs are fully charged by 7 am. Since a 24-kWh battery takes a longer time to recharge than the 16-kWh, the best time to begin off-peak rates will mainly depend upon the 24-kWh EV loads.

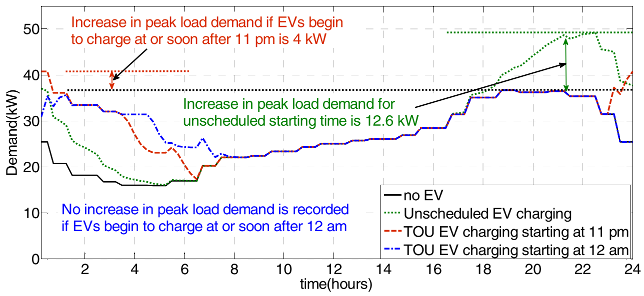

FIGURE 18. Load shape profiles with off-peak rates beginning at 11 pm and 12 am (24-kWh EVs).

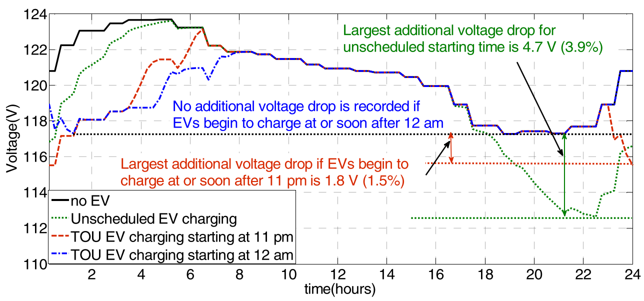

FIGURE 19. Voltage profiles with off-peak rates beginning at 11 pm and 12 am (24-kWh EVs).

The impacts of a TOU schedule beginning at 11 pm and 12 am on the 24-kWh EV loads are detailed here. Fig. 18 and Fig. 19 show the load shape profiles and voltage profiles when four 24-kWh EV loads are charging under TOU schedules beginning at 11 pm and 12 am. Upon starting off-peak rates at 11 pm, and assuming there are four 24-kWh EVs (each is equipped with a 240V/16A charger) in a given secondary service, and that most EV owners would program their vehicles to start charging at or soon after 11 pm, the largest additional voltage drop is 1.8 V (1.5%) and the increase in peak load demand is approximately 4 kW. Furthermore, on beginning off-peak rates at 11 pm, all 24-kWh EVs with an initial SOC of 20% are fully charged by 7 am. If off-peak rates begin at 12 am and most EV owners program their vehicles to start charging at or soon after 12 am, no increase in peak demand and no additional voltage drop are recorded in the secondary circuit. However, in this case, 24-kWh EV loads that begin to charge after 12:30 am, with an initial SOC of 20%, are only charged up to 90% by 7 am.

The TOU pricing scheme is a popular method of implementing time-controlled charging of EV loads. The optimal time selected to begin off-peak rates should minimize the effects of EV charging while ensuring EVs are fully charged by 7 am, thus optimizing both grid and customer benefits. Based on our analysis, we conclude that the optimal time to begin off-peak rates is between 11 pm and 12 am (midnight). Furthermore, we also demonstrate that scheduling off-peak rates at 11 pm or 12 am is a trade-off between secondary service voltage quality and customer satisfaction.

VII. SMART EV CHARGING TO MITIGATE EV LOAD IMPACTS

A TOU pricing structure can successfully shift EV charging to off-peak load hours, thus mitigating the impacts of EV charging on peak load demand and secondary voltage drops. The simultaneous charging of a large number of EV loads under a TOU schedule, however, may result in a second peak in the load demand during off-peak hours [33]. The second peak can limit the number of EVs that can be accommodated by the distribution circuit. It is observed that even after implementing TOU rates, a significant amount of distribution system capacity remains underutilized. Several studies conclude that directly controlling EV charging rates and charging start time with a smart charging algorithm may utilize the power system more efficiently. An optimal EV charging schedule can be obtained for a desired grid or customer objective. Several articles [15], [39]–[55] have proposed smart charging algorithms to directly control EV charging schedule while aiming to either maximize utility benefits or EV customers' benefits. The utility benefits are maximized by optimally shifting EV load demand to off-peak hours. As for customer benefits, methods are proposed to control EV charging while decreasing EV charging cost in a real-time electricity market.

However, the smart charging methods proposed in the literature have certain limitations. For example, by shifting EV charging to off-peak hours, the first approach ignores the convenience of EV owners. The second approach is limited in its application, as many utilities still do not deploy real-time electricity pricing for the residential customers [56]. Furthermore, none of the methods directly aim to decrease EV charging impacts on the service voltages.

In this section, a smart EV charging algorithm is proposed to minimize the voltage quality impacts of residential EV chargers. The algorithm aims to find an optimal charging schedule for each EV in the system by locally minimizing the voltage variation at each EV load node, thus flattening the service voltage profile. To avoid customer inconvenience, the algorithm takes customers' input regarding EV charging start and end times. Since the secondary wire voltage drop is caused by an increase in the load demand during EV charging, shifting the EV load demand to off-peak load hours minimizes voltage variations. Both voltage quality and service loading impacts of EV charging are mitigated this way.

The simulation results conclude that the proposed controlled charging method is efficient in mitigating both voltage drop and transformer loading concerns, even when 100% of residential loads include EV loads. Additionally, it is demonstrated that the proposed method efficiently utilizes the distribution grid compared to the TOU schedule EV charging scenario.

A. PROPOSED CHARGING ALGORITHM

The objective of the proposed charging scheme is to decrease the voltage variability in the secondary wires while EV loads are charging, thereby maintaining the feeder voltages near 1 pu. The voltage variability is defined as the sum of deviations in the voltage profile with respect to the base voltage (1 pu) over a day. From the impact analysis discussed in Section IV, it is clear that the most significant voltage drops are recorded at the load nodes supplying the EV loads. The algorithm monitors the node voltage at each EV load node over a day and minimizes the overall voltage variation by optimally controlling the charging profile of each EV load. Note that the proposed approach is deterministic and uses a day-ahead load forecast to optimize the next day's EV charging schedule.

1) PROBLEM FORMULATION

The proposed charging algorithm should minimize daily voltage variations by controlling the daily EV charging profiles. The voltage variation is the difference between the base voltage (1 pu) and the voltage at each EV load node, over a day, as shown in (1). The mathematical formulation of the problem statement is given as follows.

Let there be M electric vehicles connected to a distribution circuit, with battery capacity E_i where $i \in \{1 \cdots M\}$. The battery content of each vehicle at time t is represented by $Q_i(t)$. The battery content at any time depends upon the EV charger power level. Let EV charger power levels be represented by variable $P_i(t)$. The voltage variability is given by:

$$\boxed{V_{var}\left(t, \boldsymbol{Q}(t), \boldsymbol{P}(t)\right) = \sum_{i=1}^{M} \left(1 - V_i\left(t, \boldsymbol{Q}(t), \boldsymbol{P}(t)\right)\right) \qquad (1)}$$

where,

$$\boldsymbol{Q}(\boldsymbol{t}) = \begin{bmatrix} Q_1(t) \\ \vdots \\ Q_M(t) \end{bmatrix}, \text{ battery content of each EV at time } t,$$

$$\boldsymbol{P}(\boldsymbol{t}) = \begin{bmatrix} P_1(t) \\ \vdots \\ P_M(t) \end{bmatrix}, \text{ EV charger power level at time } t, \text{ and}$$

$V_i\left(t, \boldsymbol{Q}(t), \boldsymbol{P}(t)\right)$, is per unit voltage at time t and at the node supplying for i^{th} EV, with battery content given by $\boldsymbol{Q}(\boldsymbol{t})$ and EV charging power given by $\boldsymbol{P}(\boldsymbol{t})$.

The proposed controlled charging algorithm is formulated as an optimal control problem, where, $V_{var}(t)$ defines the cost function, and $\boldsymbol{Q}(t)$ corresponds to the state variable which evolves as per the control variable $\boldsymbol{P}(t)$. The objective is to minimize $V_{var}(t)$ over time $t \in (0, T)$, by optimizing the EV charger power levels and ensuring the batteries are completely charged at the end of the charging period $(t = T)$, where charging begins at $t = 0$. The cost function is defined as the following:

$$\boxed{J = \int_0^T V_{var}\left(t, \boldsymbol{Q}(t), \boldsymbol{P}(t)\right) dt \qquad (2)}$$

The controlled charging problem is formulated as follows:

$$\min(J)=\min\left(\int_0^T V_{var}\left(t,\boldsymbol{Q}(t),\boldsymbol{P}(t)\right)dt\right) \tag{3}$$

Subject to

$$\dot{Q}_i(t)=P_i(t) \quad \forall i\in\{1,\ldots M\}$$

For an optimal control problem, the control variable $P_i(t)$ should be bounded and integrable. Therefore, the control variable is defined as:

$$0\le P_i(t)\le P_i \quad \forall i\in\{1,\ldots M\} \tag{4}$$

where, P_i is peak charging power of the charger supplying for i^{th} EV.

The initial and terminal conditions for the state variable $Q_i(t)$ are defined next. The initial time is taken as zero and the initial and final conditions of the battery content for M vehicles are given as following.

$$\begin{aligned}Q_i(0)&=Q_{i,0} \quad \forall i\in\{1,\ldots M\}\\ Q_i(T)&=E_i \quad \forall i\in\{1,\ldots M\}\end{aligned} \tag{5}$$

where,

$Q_{i,0}$, is the initial battery content of the i^{th} EV when plugged in for charging, i.e. at $t=0$,

E_i, is the battery capacity of the fully charged i^{th} EV, where T is specified by EV owners,

$(0,T)$ is the charging period.

2) PROPOSED METHODOLOGY

This section describes the methodology to solve the EV charging problem formulated in the previous section. Since the battery charger power level could only be varied in discrete steps, the optimal control problem is discretized. Furthermore, the load flow analysis to calculate the voltage variability is also executed in discrete time steps. Therefore, a discrete optimization model is more practical.

The discrete version of the proposed EV charging problem is formulated and solved using the dynamic programming approach. The EV charging period $(0,T)$ is discretized in 15 min intervals, resulting in T time stages equal to the number of hours EVs are charging multiplied by 4. Since the EV charging study is conducted for residential chargers, EVs are connected for charging from 6 pm to 6 am (12 hours), resulting in $T=48$ time stages. The battery contents of M EVs are discretized for T stages where the battery content of i^{th} EV at time t is given by $Q_{t,i}$. The charging power level at a time step t for i^{th} EV is represented by $P_{t,i}$. Note that based on the customer input, a different time period for EV charging may be specified for the EV loads. The proposed algorithm can include the customer specified charging period thus avoiding inconveniencing the EV customers due to controlled charging.

The possible values for charging power $P_{t,i}$ are also discretized and it is assumed that $P_{t,i}$ can take three values: P_i (charger working at peak charging power), $P_i/2$ (charger working at half its peak charging power) and 0 (charger is off). The discrete charging power results in R_i discrete values for EV battery content $(Q_{t,i})$ at time t. R_i is given by (6), where P_i, is the peak charging power available at the charger supplying for the i^{th} EV and Q_i^0 is the initial battery content.

$$R_i=\frac{(E_i-Q_i^0)}{P_i/8} \tag{6}$$

The optimal control problem for EV charging formulated in the previous section is discretized (7)-(9). The discrete version of the controlled EV charging problem is expressed in a backward recursive formulation to be solved using the dynamic programming approach. Let,

$f_{t+1}\left(\boldsymbol{Q}_{t+1}\right)$, represent the total optimal voltage variability measured from time period $t+1$ to T,

$V_{var}\left(t,\boldsymbol{Q}_t,\boldsymbol{P}_t\right)$, is the voltage variability at time t with $\boldsymbol{Q}_t$ battery content and $\boldsymbol{P}_t$ EV charger power level,

$\boldsymbol{Q}_t=\begin{bmatrix}Q_{t,1}\\ \vdots\\ Q_{t,M}\end{bmatrix}$, is a M dimensional vector with each element $Q_{t,i}$ representing battery content for the i^{th} EV at time t, and

$\boldsymbol{P}_t=\begin{bmatrix}P_{t,1}\\ \vdots\\ P_{t,M}\end{bmatrix}$, is a M dimensional vector with each element $P_{t,i}$ representing EV charger power for the i^{th} EV at time t.

The problem formulation is given as follows:

$$f_t\left(\boldsymbol{Q}_t\right)=\min\left(V_{var}\left(t,\boldsymbol{Q}_t,\boldsymbol{P}_t\right)+f_{t+1}\left(\boldsymbol{Q}_{t+1}\right)\right) \qquad t=1,2\ldots T \tag{7}$$

Subject to

$$\boldsymbol{Q}_t=\boldsymbol{Q}_{t+1}-\boldsymbol{P}_t\Delta t \tag{8}$$

$$\begin{aligned}&Q_i^0\le Q_{t,i}\le E_i \quad \forall i\in 1,\ldots M\\ &P_{t,i}=\begin{cases}0\\ P_i/2 \quad \forall i\in 1,\ldots M\\ P_i\end{cases}\\ &Q_{T,i}=E_i \quad \forall i\in 1,\ldots M\end{aligned} \tag{9}$$

where,

Q_i^0 is the initial battery content,

E_i, is the battery capacity of the fully charged i^{th} EV, and

P_i, is peak charging power of the charger supplying for i^{th} EV.

The dynamic programming formulation in (7)-(9) is sequentially solved for each electric vehicle charging profile using the dynamic programming successive approximation (DPSA) method [15]. DPSA decomposes the multidimensional problem into a sequence of one-dimensional problems, each solving an optimal charge profile for an EV load.

B. EVALUATION OF THE PROPOSED CHARGING SCHEME

The proposed controlled charging scheme is evaluated for its effectiveness in mitigating voltage quality issues.

The analysis is first done for 16-kWh EV loads charged by Level-2 (240V/16A) chargers with a peak charging power (P_i) equal to 3.84 kW and 90% of charging efficiency. The initial (Q_i^0) and the final battery capacity (E_i) for each EV are 3.2 kWh (20% SOC) and 16 kWh (100% SOC), respectively. It is also assumed that each EV can start charging as early as 6 pm and must be fully charged by 6 am. Note that for all cases, the initial SOC of the vehicle is 20%. A more practical SOC for vehicles using travel statistics could be used, but since the objective of this section is to evaluate the proposed charging strategy, the starting SOC of the vehicle is irrelevant. Besides, using the minimum allowed SOC permits us to evaluate the charging strategies under the worst possible conditions.

The results for the controlled charging algorithm are compared against two cases: the uncontrolled charging scenario and the charging scenario with an optimal TOU schedule (off-peak rate beginning at 12 am). The three charging methods are compared for the number of EVs the selected distribution circuit can accommodate without violating the feeder under-voltage limit (< 0.95 pu). The number of EVs that can be accommodated by a given distribution circuit without violating the feeder under-voltage limit is referred to as the EV accommodation capacity of the circuit.

1) IMPACT ON VOLTAGE VARIABILITY DURING EV CHARGING

An example secondary circuit, which is supplied by a 13.8kV/120V distribution transformer and supplies for 8 customer loads, is selected (see Fig. 7). Four EVs are connected at the customer load locations and each EV charging method i.e. uncontrolled charging, charging with optimal TOU schedule, and proposed controlled charging, is evaluated. The load demand at the service transformer and voltage profiles at each EV load node are recorded for each charging method.

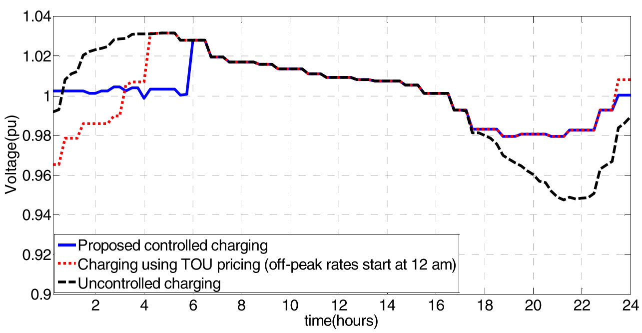

FIGURE 20. Voltage profile at the EV load location for each charging method.

The voltage profile at an EV load node for each charging method is shown in Fig. 20. The figure portrays that the proposed charging algorithm successfully minimizes the voltage variability at the EV load node and maintains the feeder voltage near 1 pu. Using the proposed charging method, the total EV load demand is optimally scheduled so that the voltage deviations at each EV load node, with respect to 1 pu, are minimized. The minimum voltages recorded at each EV load node for the three charging methods are shown in Table 10. From the customer's perspective, the proposed algorithm efficiently mitigates under-voltage concerns and flattens the feeder voltage profile.

TABLE 10. Minimum feeder voltages recorded due to EV load charging.

EV load	Minimum Voltage (pu)		
	Uncontrolled Charging	Charging with TOU pricing	Controlled Charging
EV 1	0.9611	0.9790	1.002
EV 2	0.9475	0.9654	1.00
EV 3	0.9557	0.9718	1.003
EV 4	0.9579	0.9741	1.004

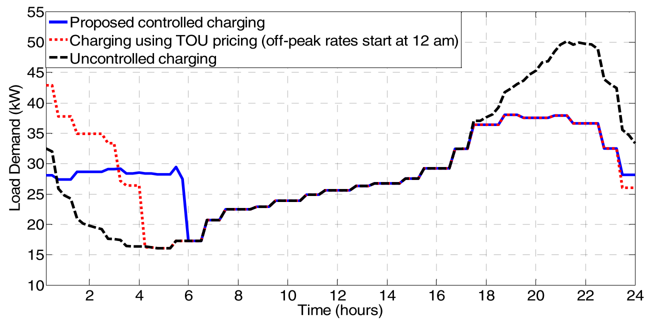

FIGURE 21. Daily load demand profile at the service transformer for each charging method.

An important observation is made when the impact of the proposed charging scheme on the service transformer load demand is assessed. The daily load demand profiles corresponding to each charging method, measured at the service transformer location, are shown in Fig. 21. The proposed charging algorithm, by filling the off-peak load demand valley, results in a flat load demand at the service transformer location. Although the optimization problem is not formulated to minimize the service transformer peak load demand, the proposed charging method efficiently shifts the EV load demand to off-peak load hours. The proposed algorithm, therefore, mitigates the service transformer load demand issues as well and is able to meet utility concerns efficiently.

As for the EV charging under an optimal TOU schedule, the EV load demand shifts to off-peak load hours, but there is a second peak in the load demand. The load demand for the second peak (42.5 MW), however, is lower than the peak demand for the uncontrolled EV charging scenario (50 kW). Note that the proposed controlled charging method results in no additional peaks in load demand while EV loads are charging.

2) EV ACCOMMODATION CAPACITY OF THE DISTRIBUTION CIRCUIT

The EV accommodation capacity of a distribution circuit is defined as the number of EVs the circuit can accommodate without violating the ANSI under-voltage limit (<0.95 pu). The EV accommodation capacity is defined for both primary and secondary wire voltages. Since the future EV charger locations are unpredictable, a stochastic analysis is required. The stochastic analysis evaluates multiple EV deployment scenarios by randomly varying EV locations and penetration percentages.

To make the stochastic analysis systematic, EV deployment scenarios are simulated in the following order [66]. First, for a 5% customer penetration level, EV loads with Level-2 240V/16A chargers and 16-kWh batteries are deployed at randomly selected customer locations. Note that customer penetration is defined as the percentage of total customer loads deployed with EV loads. The customer locations are selected by uniformly sampling the pool of secondary customers (total = 1473) supplied by the distribution feeder. Each EV charging method (uncontrolled, TOU, and smart charging) is implemented for each EV load at a given customer penetration level. A load flow analysis is carried out for each charging method and the minimum primary and secondary voltages are recorded. The customer penetration is increased in an increment of 5% and additional EV loads are deployed at the remaining customer load locations. The process is repeated until the customer penetration level reaches 100%. This gives 20 EV deployment scenarios, one at each customer penetration level (5%, 10% …100%). Next, the above process is repeated 100 times, resulting in 2000 EV deployment scenarios, 100 at each customer penetration level. A daily load flow analysis is performed on the 2000 EV deployment scenarios and the minimum voltages over a day are recorded. The above process is called a stochastic EV analysis.

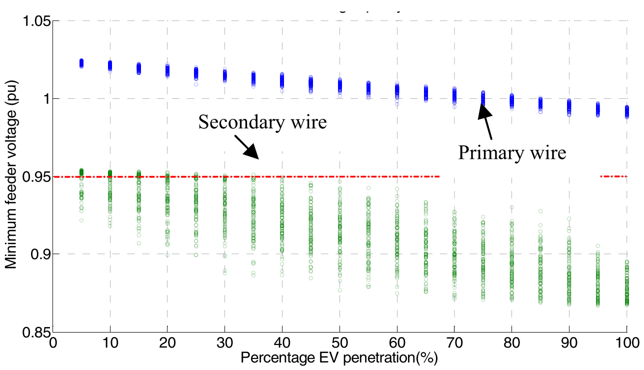

FIGURE 22. **EV accommodation capacity for the uncontrolled charging case.**

Fig. 22 shows the result of the stochastic EV analysis corresponding to the uncontrolled charging case. In Fig. 22, each point represents the result corresponding to one EV deployment scenario. The graph consists of 4000 points, 2000 points corresponding to the minimum voltages recorded for the primary and secondary wires corresponding to 2000 EV deployment scenarios. From Fig. 22, the primary wire voltages do not violate the under-voltage limit, even with 100% customer penetration. For the secondary wire voltages, the under-voltage limit is violated at the 5% customer penetration level (73 EV loads). The minimum secondary voltage decreases to 0.92 pu with 5% customer penetration and 0.87 pu with 100% customer penetration.

The EV accommodation capacity is calculated for the case when EV loads are charging under a TOU pricing schedule in which off-peak rates start at 12 am (see Fig. 23). From the figure, the first voltage violation is recorded at 10% EV penetration (147 EV loads). Thus, the TOU pricing increases the circuit's EV accommodation capacity to 10%. Furthermore, the lowest voltages recorded for each EV deployment scenario increases on implementing TOU pricing structure.

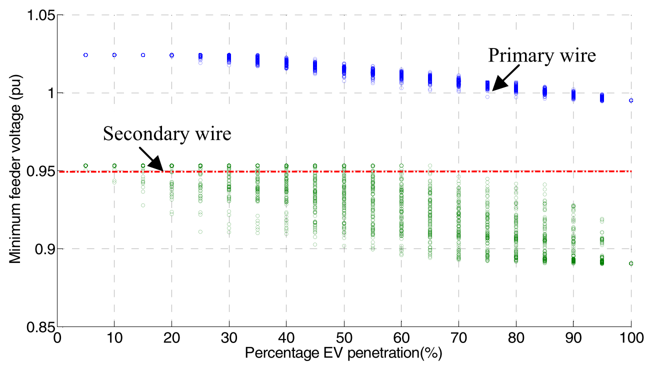

FIGURE 23. **EV accommodation capacity, when EV loads are charged under an optimal TOU schedule with off-peak rates beginning at 12 am.**

In order to understand the quantitative improvement provided by TOU pricing at the secondary voltage level, the percentages of secondary customers recording under-voltage for each EV deployment scenario are plotted for both the uncontrolled charging scenario and charging under TOU pricing schedule. Note that the percentage of secondary customers experiencing an under-voltage condition decreases significantly on implementing the TOU pricing schedule (see Fig. 24). With 100% EV penetration (1473 EV loads), the percentage of secondary customers recording an under-voltage condition decreases to 0.8% for the TOU charging case, up from 2.8% for the uncontrolled charging scenario.

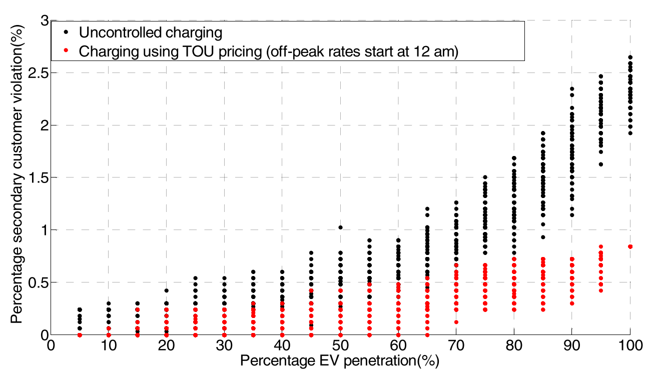

FIGURE 24. **Percentage of secondary customers reporting under-voltage violation for uncontrolled charging and for TOU controlled charging.**

TABLE 11. Comparison of the three charging methods for each EV penetration level.

Percentage EV penetration	Number of EV customers	Peak Load demand			Minimum primary voltage			Minimum secondary voltage			Number of secondary customer violation		
		Charging Method			Charging Method			Charging Method			Charging Method		
		1	2	3	1	2	3	1	2	3	1	2	3
5	73	8.02	7.77	7.77	1.020	1.024	1.024	0.922	0.951	0.953	4	0	0
10	147	8.26	7.77	7.77	1.017	1.024	1.024	0.918	0.943	0.953	5	1	0
15	220	8.51	7.77	7.77	1.016	1.024	1.024	0.907	0.928	0.953	5	4	0
20	294	8.75	7.77	7.77	1.014	1.024	1.024	0.899	0.923	0.953	7	4	0
25	368	8.98	7.77	7.77	1.009	1.019	1.024	0.899	0.911	0.953	9	4	0
30	441	9.20	7.77	7.77	1.011	1.018	1.024	0.888	0.911	0.953	9	4	0
35	515	9.47	7.91	7.77	1.007	1.017	1.024	0.886	0.910	0.953	10	5	0
40	589	9.69	8.21	7.77	1.005	1.016	1.024	0.887	0.910	0.953	10	5	0
45	662	9.93	8.52	7.77	1.004	1.012	1.024	0.885	0.903	0.953	13	7	0
50	736	10.16	8.82	7.77	1.001	1.008	1.024	0.877	0.902	0.953	17	7	0
55	810	10.40	9.13	7.77	1.000	1.006	1.024	0.879	0.900	0.953	15	8	0
60	883	10.60	9.44	7.77	0.996	1.003	1.024	0.875	0.896	0.953	15	8	0
65	957	10.84	9.75	7.77	0.999	1.002	1.024	0.876	0.894	0.953	20	9	0
70	1031	11.11	10.06	7.77	0.995	1.001	1.024	0.871	0.893	0.953	21	11	0
75	1104	11.36	10.36	7.78	0.994	0.998	1.024	0.871	0.893	0.946	25	11	1
80	1178	11.58	10.68	7.82	0.993	0.997	1.023	0.871	0.892	0.946	28	12	1
85	1252	11.79	10.99	7.85	0.991	0.996	1.023	0.869	0.891	0.946	32	12	1
90	1325	12.03	11.30	7.85	0.989	0.996	1.023	0.867	0.891	0.946	39	12	1
95	1399	12.28	11.61	7.88	0.989	0.995	1.022	0.867	0.891	0.945	41	14	1
100	1473	12.52	11.92	7.88	0.988	0.995	1.022	0.867	0.891	0.945	44	14	1

*Charging method 1 – uncontrolled charging
*Charging method 2 – charging under TOU pricing schedule (off-peak rates beginning at 12 am)
*Charging method 3 – proposed controlled charging using dynamic programming

The proposed controlled charging method using dynamic programming is evaluated for its effectiveness in increasing EV accommodation capacity of the distribution circuit. The controlled charging approach is implemented at each customer penetration level, and the results are discussed. The algorithm is implemented for the EV deployment scenario, resulting in the lowest secondary voltages at each penetration level. Using the proposed algorithm, an optimal charging schedule is determined for each EV load present in the circuit. The circuit peak load demand, minimum primary and secondary wire voltages, and the number and percentage of customers reporting under-voltage violations are recorded and compared in Table 11 for the three charging strategies.

From Table 11, the proposed charging method is able to increase the EV accommodation capacity of the selected distribution circuit to 70%. For the controlled charging case and with 100% EV penetration, only one case of secondary voltage violation is recorded at the secondary customer location. Also, the minimum voltage with 100% EV penetration is only 0.946 pu, as compared with 0.891 pu for the charging scenario using TOU pricing, and 0.867 pu for the uncontrolled charging scenario. Furthermore, until 70% EV penetration, no additional peak load demand is recorded at the substation transformer on charging EV loads using the proposed algorithm.

The peak load demand recorded at the substation transformer without any EV load is 7.77 MW. It should be noted that when EV charging is done under optimal TOU schedule, no additional peak load demand is recorded until 30% EV penetration. Therefore, the optimal TOU schedule is able to mitigate the load demand concerns until 30% EV penetration. If EV load penetration is increased beyond 30%, a second peak in the substation load demand appears during off-peak load hours. From Table 11, the proposed charging method is able to accommodate up to 70% of EV without increasing the substation transformer's peak load demand.

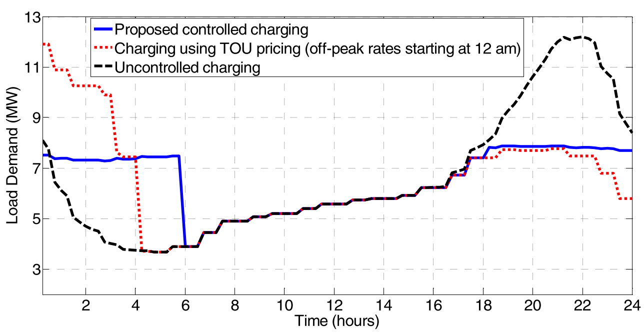

FIGURE 25. Load demand at the substation with 100% EV penetration.

To further understand the impacts of three charging schemes on substation load demand, the load demand profiles at the 100% customer penetration level is recorded (see Fig. 25). For the uncontrolled charging case, the peak load demand with EV charging increases to 12.5 MW from 7.7 MW (without any EV). As for the case with EV charging under TOU pricing, at 100% customer penetration, a significantly large second peak (at midnight) in load demand is recorded (11.9 MW). The proposed controlled charging algorithm performs the best, and even at 100% customer penetration, the load demand increases to only 7.88 MW from 7.77 MW.

3) DISCUSSION

In sum, the proposed controlled charging algorithm is efficient in mitigating the customer under-voltage concerns resulting from residential EV chargers. The algorithm works on the principle of locally minimizing the voltage variation at each EV load node, thus flattening the service voltage profile. EV charging schedules are optimized using dynamic programming while considering the daily variations in load demand profile and EV charging characteristics. Depending upon the feeder voltage, customer load demand, and EV load demand an optimal charging schedule is obtained for each EV while minimizing variations in the customer voltage profiles. Customer inconvenience is avoided as EV charging start and end times are decided by EV owners.

The minimum secondary voltage and the number of customers observing violations for each charging scenario are summarized in Fig. 26. It is concluded from the figure that the proposed charging method successfully increases the magnitude of the lowest feeder voltage and significantly decreases the number of under-voltage violations. Moreover, the proposed charging method is demonstrated to be efficient in mitigating both voltage drop and transformer loading concerns, even when 100% of residential loads include EV loads. Finally, the results demonstrate that by optimally scheduling EV charging, the proposed method utilizes the distribution grid more efficiently as compared to the TOU schedule EV charging scenario.

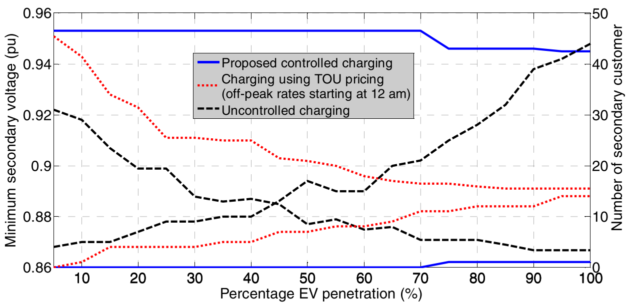

FIGURE 26. **Comparison of the three charging methods for each EV penetration level.**

VIII. CONCLUSION

This paper thoroughly evaluated the impacts of residential EV charging on distribution circuit voltages and techniques for mitigating these impacts. Our analysis shows that residential EV charging will affect secondary circuit voltages more than the primary wires. Furthermore, if a controlled charging method is not deployed, a higher EV load penetration may increase peak load demand and cause secondary service voltage drops. The impact analysis was done for both NA and EU distribution circuits.

The local and global circuit analyses for the selected distribution circuit conclude the following:

1. Additional voltage drops, caused by EV load charging, are not affected by the location of the secondary service in relation to the substation transformer.
2. EV loads closer to the service transformer decrease the additional voltage drops when compared to EV loads farther from the service transformer.
3. Doubling the size of an EV charger, or adding an EV load adjacent to the existing EV load, almost doubles the additional voltage drop.
4. Increasing EV load penetration may significantly increase voltage drops in the secondary wires, as compared to the primary wires. The feeder voltage drops, however, follow a Gaussian curve, suggesting fewer feeders have very low and very high voltage drops.
5. EV load clustering results in an unbalance in the load demand thus increasing the voltages at a few secondary service locations.
6. For a typical NA distribution circuit, EV charging mostly affects service voltages due to low short-circuit (SC) capacities; the EU tri-phase circuit is mostly affected due to the single-phase EV charging resulting in voltage asymmetry.

This report also evaluated several infrastructural upgrades implemented to mitigate EV charging concerns. The analysis concludes that increasing the size of service transformer is unable to mitigate feeder voltage drop concerns. The additional voltage drops due to EV load charging are efficiently mitigated by upgrading the distribution circuit using an additional transformer; however, the method requires infrastructural changes and hence is expensive. Implementing a TOU schedule efficiently shifts the EV load charging to off-peak load hours. Furthermore, the paper concludes that the optimal time to begin off-peak rates is between 11 pm and 12 am; the optimal time is a trade-off between utility benefits and customer inconvenience. The proposed optimal TOU schedule performed well up to 30% customer penetration with EV but resulted in a second peak in load demand on further increasing the EV load penetration.

A controlled charging algorithm is also proposed to mitigate the voltage quality problems caused by EV charging. The algorithm minimizes the voltage variations at each EV load node while taking customer inconvenience into account. An optimal EV charging profile is determined for each EV load by minimizing the overall voltage variation. The algorithm is validated for its effectiveness in mitigating loading and voltage concerns. We conclude that the proposed method significantly decreases the substation load demand by optimally shifting the EV load demand to off-peak load hours. Although designed to mitigate voltage variability issues at the secondary customer location, the algorithm is successfully able to deliver utility benefits by minimizing the substation peak load demand.

ACKNOWLEDGMENT

The authors gratefully acknowledge Mr. Aymen Lpizra, Mr. Robert Manning, Mr. Marek Waclawiack, and Mr. Matthew P. Cloud for discussions and insights into the problem, identifying distribution circuits and providing data. They would like to thank Dr. S. Bohn and Dr. M. Agsten for sharing the results regarding the EV impact study done on the European grid.

REFERENCES

[1] (2010). *U.S. Department of Energy Multi-Year Program Plan 2011–2015: Vehicle Technologies Program*. [Online]. Available: https://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/vt_mypp_2011-2015.pdf

[2] (Oct. 2012). *Metropolitan Washington Council of Governments: Electric Vehicles in Metropolitan Washington*. [Online]. Available: http://www.mwcog.org/store/item.asp?PUBLICATION_ID=449

[3] C. Farmer, P. Hines, J. Dowds, and S. Blumsack, "Modeling the impact of increasing PHEV loads on the distribution infrastructure," in *Proc. 43rd Hawaii Int. Conf. Syst. Sci. (HICSS)*, Jan. 2010, pp. 1–10.

[4] C. Roe, E. Farantatos, J. Meisel, A. P. Meliopoulos, and T. Overbye, "Power system level impacts of PHEVs," in *Proc. 42nd Hawaii Int. Conf. Syst. Sci. (HICSS)*, Jan. 2009, pp. 1–10.

[5] J. Taylor, A. Maitra, M. Alexander, D. Brooks, and M. Duvall, "Evaluation of the impact of plug-in electric vehicle loading on distribution system operations," in *Proc. IEEE Power Energy Soc. General Meeting*, Jul. 2009, pp. 1–6.

[6] J. Taylor, A. Maitra, M. Alexander, D. Brooks, and M. Duvall, "Evaluations of plug-in electric vehicle distribution system impacts," in *Proc. IEEE Power Energy Soc. General Meeting*, Jul. 2010, pp. 1–6.

[7] S. Rahman and G. B. Shrestha, "An investigation into the impact of electric vehicle load on the electric utility distribution system," *IEEE Trans. Power Del.*, vol. 8, no. 2, pp. 591–597, Apr. 1993.

[8] J. Taylor, J. W. Smith, and R. Dugan, "Distribution modeling requirements for integration of PV, PEV, and storage in a smart grid environment," in *Proc. IEEE Power Energy Soc. General Meeting*, Jul. 2011, pp. 1–6.

[9] A. Hajimiragha, C. A. Canizares, M. W. Fowler, and A. Elkamel, "Optimal transition to plug-in hybrid electric vehicles in Ontario, Canada, considering the electricity-grid limitations," *IEEE Trans. Ind. Electron.*, vol. 57, no. 2, pp. 690–701, Feb. 2010.

[10] Y. Chen, A. Oudalov, and J. S. Wang, "Integration of electric vehicle charging system into distribution network," in *Proc. IEEE 8th Int. Conf. Power Electron. ECCE Asia (ICPE & ECCE)*, May/Jun. 2011, pp. 593–598.

[11] S. W. Hadley, "Evaluating the impact of plug-in hybrid electric vehicles on regional electricity supplies," in *Proc. iREP Symp.*, Aug. 2007, pp. 1–12.

[12] J. C. Gomez and M. M. Morcos, "Impact of EV battery chargers on the power quality of distribution systems," *IEEE Trans. Power Del.*, vol. 18, no. 3, pp. 975–981, Jul. 2003.

[13] S. Shao, M. Pipattanasomporn, and S. Rahman, "Challenges of PHEV penetration to the residential distribution network," in *Proc. IEEE Power Energy Soc. General Meeting*, Jul. 2009, pp. 1–8.

[14] O. Warweg, F. Schaller, S. Ritter, and P. Bretschneider, "Technical and regulatory challenges for the integration of electric vehicles into the energy system," in *Proc. 2nd IEEE PES Int. Conf. Exhibit. Innov. Smart Grid Technol. (ISGT Europe)*, Dec. 2011, pp. 1–8.

[15] K. Clement-Nyns, E. Haesen, and J. Driesen, "The impact of charging plug-in hybrid electric vehicles on a residential distribution grid," *IEEE Trans. Power Syst.*, vol. 25, no. 1, pp. 371–380, Feb. 2010.

[16] F. Koyanagi, T. Inuzuka, Y. Uriu, and R. Yokoyama, "Monte Carlo simulation on the demand impact by quick chargers for electric vehicles," in *Proc. IEEE Power Eng. Soc. Summer Meeting*, vol. 2. Jul. 1999, pp. 1031–1036.

[17] A. G. Boulanger, A. C. Chu, S. Maxx, and D. L. Waltz, "Vehicle electrification: Status and issues," *Proc. IEEE*, vol. 99, no. 6, pp. 1116–1138, Jun. 2011.

[18] Q. Wu, A. H. Nielsen, J. Ostergaard, S. T. Cha, and Y. Ding, "Impact study of electric vehicle (EV) integration on medium voltage (MV) grids," in *Proc. 2nd IEEE PES Int. Conf. Exhibit. Innov. Smart Grid Technol. (ISGT Europe)*, Dec. 2011, pp. 1–7.

[19] J. R. Pillai and B. Bak-Jensen, "Impacts of electric vehicle loads on power distribution systems," in *Proc. IEEE Vehicle Power Propuls. Conf. (VPPC)*, Sep. 2010, pp. 1–6.

[20] G. A. Putrus, P. Suwanapingkarl, D. Johnston, E. C. Bentley, and M. Narayana, "Impact of electric vehicles on power distribution networks," in *Proc. IEEE Vehicle Power Propuls. Conf. (VPPC)*, Sep. 2009, pp. 827–831.

[21] A. Dubey, S. Santoso, and M. P. Cloud, "Understanding the effects of electric vehicle charging on the distribution voltages," in *Proc. IEEE Power Energy Soc. General Meeting*, Jul. 2013, pp. 1–5.

[22] A. Dubey, "Impact of electric vehicle loads on utility distribution network voltages," M.S. thesis, Dept. Elect. Comput. Eng., Univ. Texas, Austin, TX, USA, 2012.

[23] A. Dubey, S. Santoso, and M. P. Cloud, "A practical approach to evaluate voltage quality effects of electric vehicle charging," in *Proc. Int. Conf. Connected Vehicles Expo.*, Dec. 2013, pp. 188–194.

[24] A. Dubey, S. Santoso, and M. P. Cloud, "Comparative analysis of effects of electric vehicle loads on distribution system voltages," in *Proc. IEEE PES Transmiss. Distrib. Conf. Expo.*, Apr. 2013, pp. 1–5.

[25] Electric Power Research Institute. (2011). *Transportation Electrification: A Technology Overview*. [Online]. Available: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001021334/

[26] R.-C. Leou, C.-L. Su, and C.-N. Lu, "Stochastic analyses of electric vehicle charging impacts on distribution network," *IEEE Trans. Power Syst.*, vol. 29, no. 3, pp. 1055–1063, May 2014.

[27] M. K. Gray and W. G. Morsi, "Power quality assessment in distribution systems embedded with plug-in hybrid and battery electric vehicles," *IEEE Trans. Power Syst.*, vol. 30, no. 2, pp. 663–671, Mar. 2015.

[28] S. Bohn, M. Agsten, A. Dubey, and S. Santoso, "A comparative analysis of PEV charging impacts—An international perspective," in *Proc. SAE Word Congr. Exhibit.*, Detroit, MI, USA, Apr. 2015, pp. 1–10.

[29] C. Weiller, "Plug-in hybrid electric vehicle impacts on hourly electricity demand in the United States," *Energy Policy*, vol. 39, no. 6, pp. 3766–3778, 2011.

[30] J. Axsen and K. Kurani, "The early U.S. market for PHEVs: Anticipating consumer awareness, recharge potential, design priorities and energy impacts," Inst. Transp. Studies, Univ. California, Davis, CA, USA, Tech. Rep. UCD-ITS-RR-08-22, 2008.

[31] K. Parks, P. Denholm, and T. Markel, "Costs and emissions associated with plug-in hybrid electric vehicle charging in the Xcel Energy Colorado service territory," Nat. Renew. Energy Lab., Golden, CO, USA, Tech. Rep. NREL/TP-640-41410, 2007.

[32] J. Cook, C. Churchwell, and S. George. (2014). *Final Evaluation of San Diego Gas & Electric Plug-In Electrical Vehicle TOU*. San Diego Gas & Electric. [Online]. Available: https://www.sdge.com/sites/default/files/documents/1681437983/SDGE%20EV%20%20Pricing%20%26%20Tech%20Study.pdf

[33] S. Schey, D. Scoffield, and J. Smart, "A first look at the impact of electric vehicle charging on the electric grid in the EV project," in *Proc. EVS26 Int. Battery, Hybrid, Fuel Cell Electr. Vehicle Symp.*, Los Angeles, CA, USA, May 2012, pp. 1–12.

[34] S. Shao, T. Zhang, M. Pipattanasomporn, and S. Rahman, "Impact of TOU rates on distribution load shapes in a smart grid with PHEV penetration," in *Proc. IEEE PES Transmiss. Distrib. Conf. Expo.*, Apr. 2010, pp. 1–6.

[35] Y. Gao, C. Wang, Z. Wang, and H. Liang, "Research on time-of-use price applying to electric vehicles charging," in *Proc. IEEE Innov. Smart Grid Technol.-Asia (ISGT Asia)*, May 2012, pp. 1–6.

[36] A. Dubey, S. Santoso, M. P. Cloud, and M. Waclawiak, "Determining time-of-use schedules for electric vehicle loads: A practical perspective," *IEEE Power Energy Technol. Syst. J.*, vol. 2, no. 1, pp. 12–20, Mar. 2015.

[37] S. W. Hadley. (Oct. 2006). "Impact of plug-in hybrid vehicles on the electric grid," Oak Ridge Nat. Lab., Oak Ridge, TN, USA, Tech. Rep. ORNL/TM-2006/554. [Online]. Available: http://www.ornl.info/info/ornlreview/v40_2_07/2007_plug-in_paper.pdf

[38] P. Denholm and W. Short, "An evaluation of utility system impacts and benefits of optimally dispatched plug-in hybrid electric vehicles," Nat. Renew. Energy Lab., Golden, CO, USA, Tech. Rep. NREL/TP-620-40293, 2006.

[39] K. Mets, T. Verschueren, W. Haerick, C. Develder, and F. De Turck, "Optimizing smart energy control strategies for plug-in hybrid electric vehicle charging," in *Proc. IEEE/IFIP Netw. Oper. Manage. Symp. Workshops*, Apr. 2010, pp. 293–299.

[40] E. Sortomme, M. M. Hindi, S. D. J. MacPherson, and S. S. Venkata, "Coordinated charging of plug-in hybrid electric vehicles to minimize distribution system losses," *IEEE Trans. Smart Grid*, vol. 2, no. 1, pp. 198–205, Mar. 2011.

[41] S. Deilami, A. S. Masoum, P. S. Moses, and M. A. S. Masoum, "Real-time coordination of plug-in electric vehicle charging in smart grids to minimize power losses and improve voltage profile," *IEEE Trans. Smart Grid*, vol. 2, no. 3, pp. 456–467, Sep. 2011.

[42] S. Shao, M. Pipattanasomporn, and S. Rahman, "Demand response as a load shaping tool in an intelligent grid with electric vehicles," *IEEE Trans. Smart Grid*, vol. 2, no. 4, pp. 624–631, Dec. 2011.

[43] S. Shao, M. Pipattanasomporn, and S. Rahman, "Grid integration of electric vehicles and demand response with customer choice," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 543–550, Mar. 2012.

[44] L. Gan, U. Topcu, and S. H. Low, "Stochastic distributed protocol for electric vehicle charging with discrete charging rate," in *Proc. IEEE Power Energy Soc. General Meeting*, Jul. 2012, pp. 1–8.

[45] S. Han, S. Han, and K. Sezaki, "Development of an optimal vehicle-to-grid aggregator for frequency regulation," *IEEE Trans. Smart Grid*, vol. 1, no. 1, pp. 65–72, Jun. 2010.

[46] E. Sortomme and M. A. El-Sharkawi, "Optimal scheduling of vehicle-to-grid energy and ancillary services," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 351–359, Mar. 2012.

[47] J. de Hoog, T. Alpcan, M. Brazil, D. A. Thomas, and I. Mareels, "Optimal charging of electric vehicles taking distribution network constraints into account," *IEEE Trans. Power Syst.*, vol. 30, no. 1, pp. 365–375, Jan. 2015.

[48] Z. Li, Q. Guo, H. Sun, S. Xin, and J. Wang, "A new real-time smart-charging method considering expected electric vehicle fleet connections," *IEEE Trans. Power Syst.*, vol. 29, no. 6, pp. 3114–3115, Nov. 2014.

[49] T. Markel, M. Kuss, and P. Denholm, "Communication and control of electric drive vehicles supporting renewables," in *Proc. IEEE Vehicle Power Propuls. Conf. (VPPC)*, Sep. 2009, pp. 27–34.

[50] G. B. Shrestha and B. C. Chew, "Study on the optimization of charge-discharge cycle of electric vehicle batteries in the context of Singapore," in *Proc. Australasian Univ. Power Eng. Conf. (AUPEC)*, Dec. 2007, pp. 1–7.

[51] Y. Cao *et al.*, "An optimized EV charging model considering TOU price and SOC curve," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 388–393, Mar. 2012.

[52] W. Shi and V. W. S. Wong, "Real-time vehicle-to-grid control algorithm under price uncertainty," in *Proc. IEEE Int. Conf. Smart Grid Commun. (SmartGridComm)*, Oct. 2011, pp. 261–266.

[53] Y. He, B. Venkatesh, and L. Guan, "Optimal scheduling for charging and discharging of electric vehicles," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1095–1105, Sep. 2012.

[54] C. Jin, J. Tang, and P. Ghosh, "Optimizing electric vehicle charging: A customer's perspective," *IEEE Trans. Veh. Technol.*, vol. 62, no. 7, pp. 2919–2927, Sep. 2013.

[55] P. Richardson, D. Flynn, and A. Keane, "Local versus centralized charging strategies for electric vehicles in low voltage distribution systems," *IEEE Trans. Smart Grid*, vol. 3, no. 2, pp. 1020–1028, Jun. 2011.

[56] P. L. Joskow and C. D. Wolfram, "Dynamic pricing of electricity," *Amer. Econ. Rev.*, vol. 102, no. 3, pp. 381–385, 2012.

[57] D. A. Corrigan and A. Masias, "Batteries for electric and hybrid vehicles," in *Linden's Handbook of Batteries*, 4th ed. New York, NY, USA: McGraw-Hill, 2011.

[58] *Plugs, Socket-Outlets, Vehicle Connectors and Vehicle Inlets—Conductive Charging of Electric Vehicles*, IEC Standard 62196, 2014.

[59] *SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler*, SAE Standard J1772, 2013.

[60] *Electric Vehicle Conductive Charging System*, IEC Standard 61851, 2011.

[61] *American National Standard for Electric Power Systems and Equipment—Voltage Ratings (60 Hertz)*, ANSI Standard C84.1-2011, 2011.

[62] *Voltage Characteristics of Electricity Supplied by Public Distribution Networks*, ISO Standard DIN EN 50160, 2011.

[63] *The United Illuminating Company*. [Online]. Available: http://www.uinet.com

[64] *Nissan Leaf*. [Online]. Available: http://www.nissanusa.com/leaf-electric-car/index#/leaf-electric-car/index

[65] *Chevrolet Volt*. [Online]. Available: http://www.chevrolet.com/volt-electric-car/

[66] J. Smith. (Dec. 2012). *Stochastic Analysis to Determine Feeder Hosting Capacity for Distributed Solar PV*. EPRI. [Online]. Available: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001026640

ANAMIKA DUBEY (S'11) received the bachelor's degree in electrical engineering from IIT Roorkee, in 2010, and the M.S.E. degree in electrical and computer engineering from The University of Texas at Austin, in 2012, where she is currently pursuing the Ph.D. degree with the Department of Electrical and Computer Engineering. Her research interests include distribution system analysis, electric vehicle technology, and grid integration of Photovoltaic (PV) generation and energy storage systems.

SURYA SANTOSO (F'14) received the M.S.E. and Ph.D. degrees from The University of Texas at Austin, in 1994 and 1996, respectively. He has been a Professor with The University of Texas at Austin since 2003. He has co-authored the book entitled *Electrical Power Systems Quality—Third Edition* (McGraw-Hill) and authored the book entitled *Fundamental of Electric Power Quality* (2013). His research interests lie in the broad area of electric power quality and wind power integration.